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RAILROAD ENGINEERING

PART III

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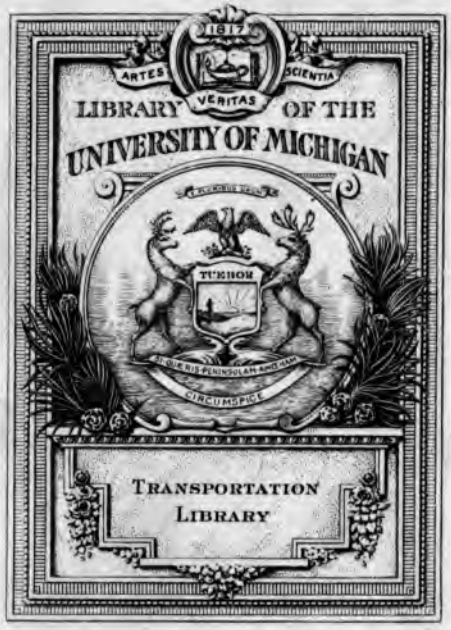
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RAILROAD ENGINEERING

PART III

INSTRUCTION PAPER

PREPARED BY

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AMERICAN SCHOOL OF CORRESPONDENCE

CHICAGO ILLINOIS

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RAILROAD ENGINEERING

PART III

ECONOMICS

RAILROAD FINANCES

159. Capitalization. Practically all of the following statements regarding capitalization, etc., of the railroads of the country are taken from the reports of the Interstate Commerce Commission and may, therefore, be considered as reliable as any which are obtainable. Many of the following figures are taken from the report for the year ending June 30, 1912. At that time the capital stock was given as $8,622,400,821. Disregarding the fractions of millions, the funded debt, expressed in millions, was 11,130, or a total capitalization of 19,752 million dollars. This represents approximately one-tenth of the national wealth. The "investment in road and equipment", to June 30, 1912, was stated as 16,004 millions. Unfortunately the finances of railroads have been so manipulated that any statement of "cost of road" does not usually represent the capital actually spent on construction.

The above figures apply to 237,467 miles of line, the total mileage being nearly 247,000 miles. The railroads directly employed 1,716,380 employes, to whom they paid over $1,252,000,000, which was over 44 per cent of the operating revenues, amounting to more than $2,842,000,000. The employes represent a population of perhaps eight millions who are directly dependent on the railroads for support. Considering the industries, such as locomotive and car shops, which depend entirely on railroads for business, and also the industries, such as steel mills and bridge works, which have railroads as their largest customers, it may perhaps be estimated that one-fourth of the entire population of the country are directly or indirectly dependent for their support on railroads.

If the argument is carried still further and the fact is recognized that a very large proportion of the products of agriculture,

mines, and manufactories could not otherwise be transported to consumers, or would not be utilized and, therefore, would not be produced, the debt of the country to railroad transportation may be better appreciated.

Although the stocks and bonds of many of the smaller railroads are owned by large corporations in their corporate capacity, yet of the total of 19,752 millions of stocks and bonds outstanding in 1912, 13,986 millions, or about 71 per cent, were owned by "other than railroad corporations"—chiefly private investors. On the basis of total assets of 19,752 million dollars and an estimated population of 95,172,000 people, the *average* ownership is over $207 per head of population. The total operating revenue of over $2,842,000,000 represents an average payment of nearly $30 per inhabitant, for the year. The "number of passengers carried one mile" was 33,132,000,000, which means that the *average* passenger traveled 348 miles during the year. The average number of passengers on a train was 53 and they traveled an average journey of 33.18 miles.

The "number of tons of freight carried one mile" was 264,080,000,000, which means that the *average* inhabitant supplied a freight business equivalent to moving 2775 tons one mile, or moving one ton 2775 miles, or moving 50 tons 55 miles. As an aid to grasping this perhaps incredible statement combined with the statement of an average annual payment of $30 per inhabitant, it should be remembered that whenever a ton of coal or even a pound of sugar is bought, the price paid includes payment made to a railroad company for freight.

While the above figures must be considered simply as averages, and not necessarily applicable to any one road, they give some idea of the magnitude of railroad business and what the *average* railroad may be expected to do. Considering, however, that the great railroads of the country are already built, and that the roads yet to be built will probably be of minor importance, even such an average statement could hardly apply to any new enterprise except with a very large discount.

160. Stocks and Bonds. An ordinary mercantile business, or even an ordinary factory is conducted on the capital directly furnished by the owner or owners. Therefore any profit over

the operating expenses may be applied as dividends no matter how small the percentage. Very few of the railroads of this country have been constructed, even approximately, on this basis. Usually a large part of the virtual ownership of a railroad is represented by bonds. The limit of the issue of the bonds may be that which expresses the confidence of the public in the enterprise, or, in other words, the value which it is assumed that the whole property could be sold for under a foreclosure sale.

During the early history of railroading, when railroads were being run through well-established communities which were without railroad facilities, the success of the enterprises seemed so certain that little or no difficulty was experienced in borrowing on bonds capital sufficient, and even more than sufficient, to construct and equip the road complete. But such opportunities are practically past. The capital stock actually paid in represents the margin, or the uncertainty between what it actually will cost to build the road and its estimated foreclosure value. The nominal issue of stock is usually about equal to the issue of bonds. In 1912, the ratio was 86 to 111.

At its best, the inception of such an enterprise means a considerable outlay of money. A group of men, acting on the belief that a road passing through certain towns will be a profitable enterprise, forms a temporary organization, develops the enterprise, has surveys made, and then if the developed plans still look encouraging, has bonds engraved and placed on the money market for sale, usually through a financial syndicate. Even if it were possible to raise enough money for actual construction, the amount of money required for this preliminary work, although but a small percentage of the gross amount required, is sometimes a large sum of money.

The gross amount required is increased by the frequently ignored fact that a road does not attain its "normal" traffic for five or ten years after it begins operation, and unless it has sufficient funds as "working capital" to tide over the initial period when it does not perhaps pay operating expenses, it is very apt to go into the hands of a receiver.

Stocks and bonds may therefore be considered as representing two forms of ownership. The interest on the bonds is a lien on the receipts, after the operating expenses have been paid. Such

interest must be paid in full before any dividends on stock may be paid. The security of the bonds is therefore comparatively good, and the profit comparatively certain although it is small.

On the other hand, the stocks are much more speculative. No dividends are paid until the operating expenses and the bond interest are fully paid; and if the latter is not paid, the bondholders have a right to demand that a "receiver" be appointed and if necessary that the road be sold. Since such a sale will not usually realize more than the face value of the bonds (and sometimes not even that), the stockholders may lose their entire investment. But if the road makes money, the excess which may be allowed for dividends may be a very large return on the amount of capital *actually paid in*. It may very easily be shown that a comparatively small change in the amount of business done may suffice to change a good profit for the stockholders into an actual deficit, which makes a receivership dangerously probable.

The relative profit on stocks and bonds and the fact that railroad securities, although sometimes very profitable, are very precarious in value is shown by the following statements: The year ending June 30, 1902, was the best year (up to that time) ever known in the railroad business. But, in spite of this, 44.6 per cent of all railroad stocks then in existence paid *no* dividends. The average rate paid on dividend-paying stock was only 5.55 per cent. Even granting that much of railroad stock is "watered"—which means essentially that it represents little or no cash actually paid in—the fact remains that during that year 44.6 per cent of all the stock issued paid no dividends. From 1895 to 1897, over 70 per cent of all railroad stocks paid no dividends.

The record regarding bonds is much better, the percentage of the entire bond issue which failed to pay anything during 1901–2 being less than 5 per cent. While it is true, almost without exception, that a railroad builds up the section of country through which it passes and increases its value far beyond the cost of the road, yet it is also true that very few roads which are old enough to have a history have escaped a receivership at some time in their growth, even though they may now be gilt-edged properties.

161. Gross Revenue. The estimation of the probable volume of traffic or the gross revenue of a proposed road can only be approx-

imated at best and even this requires experience. Since it requires five years or more for a road to attain its normal traffic, investors should not be disappointed when the returns for the first few years are less than those anticipated.

The only practicable method of estimating traffic is to study the resources of the belt of country which will be tributary to the proposed line, estimating the business obtainable from every factory, mine, blast furnace, farm, village, etc. When, as is usual, the line passes through or reaches cities which are already supplied with railroad facilities, the detailed computation of business becomes very uncertain. But if the chief business of the road is to develop local business along a route which has no other means of communication, then the computation is easier. The two dangers in the method lie in the entire neglect to allow for certain important sources of income and, on the other hand, to overestimate the income from a certain source. Analogous to the last is the neglect to allow for present or future competition, which may practically cut off sources of income.

Although some idea of the product of factories and mines may be obtained from records as to their present or prospective output, the income from passenger business can only be computed from comparisons with other roads. The freight business is generally two-thirds of the business of a road, except on those roads which have an enormous suburban traffic. The average receipts per passenger mile are about 2 cents, but it is the enormous commuter business and the growth of travel on 1000-mile tickets which bring down the average to this figure from the usual charge of 3 cents per mile and the even higher charges on roads with light traffic and very heavy expenses.

As a rough check on the above method the annual reports of the Interstate Commerce Commission give the gross earnings from operation for the road in each of three sections into which the country has been divided. Dividing this gross value by the population of the section (which is deducible from the report) an *average* value per head of population for that section is obtainable. The value for the whole United States is, as previously stated, nearly $30, but the value for some one section may prove quite different from this. Multiplying the value obtained by the population

which may be considered as tributary to the route of the road, we have a very approximate value for the income of the road. The two obvious weaknesses of the method are that the receipts of the proposed road may prove very different from the average for that section and also that the computation of the tributary population is a very uncertain calculation. But since the method may be easily tried, it furnishes a check of some value.

As a better check there are usually one or more roads which may be selected which have substantially the same characteristics and whose incomes per mile of road are nearly equal and which supposedly equal the expected income of the proposed line. Assuming the existence of such roads and that the engineer has sound judgment in estimating their characteristics, this method should be employed if possible, at least to check the value of any other computation.

The number of passengers per train is of course very uncertain. The average number of passengers carried for each passenger-train-mile, as previously stated, was 53, which is less than a car load. And when it is considered that even this average includes the heavy traffic roads and the well-filled trains on suburban roads, the average number on a light-traffic road must be very small. The number of passenger trains per day bears but little relation to the number that can be carried in one train load—as the above (53) shows.

The passenger business must be developed, coaxed, and encouraged, which can only be done by a frequency of service which is usually far ahead of the requirements from a mere hauling standpoint. It is a very poor road which cannot afford two passenger trains per day each way. The total number of passengers carried might not suffice to fill one car, but it would probably be a far greater number than would be hauled if there were only one train per day. The criterion for an increase in number would appear to be as follows:

When it may be shown that the increase in facilities due to an additional train will so encourage traffic that the additional receipts will equal or exceed the cost of the additional train (which will be less than the average cost per train-mile), then the added train will evidently be justified.

The average revenue per passenger-train-mile for 1912 was

given as $1.29, which includes receipts from mail and express, as well as passenger receipts. The average receipts per freight-train-mile was $3.02, or more than twice as much, and this, in spite of the fact that a passenger, weighing perhaps 150 pounds, paid 1.987 cents per mile, while a ton of freight paid 0.744 cent per mile. This great difference is partly due to the fact that the ratio of dead load to live load in freight is about 1 : 2, but on passenger trains it may be 5 : 1 or even 10 : 1. Another reason is that freight trains are made up, if possible, so that each engine is hauling about the limiting number of cars that it can handle (so as to reduce the number of trains required) while, as stated above, passenger trains are run frequently, and light, so as to encourage the passenger traffic.

162. Monopoly in Railroad Business. One danger to be considered in the estimating of gross revenue, and also in the subsequent designing of the road and in the facilities offered for traffic, is the assumption that the road "will have all the traffic there is". Even ignoring the effect of possible future competition, which may be encouraged and somewhat developed by a marked lack of facilities on an existing road, it should be recognized that a large part of the traffic depends directly on the facilities offered. A factory's very existence depends on its ability to collect its raw material, manufacture it, and deliver it at the door of the average consumer, perhaps in a distant city, as cheaply as other manufacturers of the same article. Under close competition, an increase in one single item of expense, such as cartage from the factory to the railroad, may make up the difference between profit and loss.

The ideal location for a railroad is that it shall pass through the heart of the manufacturing district of any city and that its passenger station shall be located in the immediate neighborhood of the business center of the city. The purchase of such property for tracks and stations after the city is well established is of course very expensive, but the disadvantages of a location which is considerably removed from the ideal location are very great. These disadvantages are so increased under competition that a road's traffic may be practically ruined. Even the passenger business is greatly affected. The passengers who will travel anyway regardless of inconveniences are comparatively few.

The most important practical feature of this question lies in the fact, referred to before, that the margin between profit and loss is very small, that a very large proportion of the gross revenue must be paid out for operating expenses, that nearly all, if not quite all, of the remainder goes to pay interest on the bonds and only a small, doubtful percentage remains for dividends. Therefore, the dividends come literally from the unnecessary traffic which must be coaxed and which will not travel on a road which lacks conveniences.

The force of this may be seen still more by considering the easy financial condition of a well-established road. The receipts are large and are partly spent in creating still further conveniences, commodious and convenient stations, better rolling stock, etc. These in turn encourage more traffic, which still further increases receipts, until there seems to be no end to the financial ability of the road. Such roads are the Pennsylvania, the New York Central, and some others. On the other hand, the poverty of a road begets a poverty of service which still further decreases receipts until ruin is in sight. Many a road has been practically compelled to supply free cartage for freight (or allow for it by a rebate) to compensate for an inconvenient freight station. Since the Interstate Commerce regulations now prevent rebates, railroads having inconvenient locations for stations or terminals do not have even that method of compensating their handicaps. The enormous sums paid to bring passenger terminals into the heart of a great city are instructive examples in this respect.

163. Division of Gross Revenue. Of the more than 2000 railroad corporations listed by the Interstate Commerce Commission, a very large number of them are so merged with the corporations operating them that their separate existence is only evident on paper. The capital stock of many of them is partially or entirely owned by the operating company and they are operated under a great variety of leases, etc. It is therefore difficult to obtain from the financial statement of any of the large corporations the division of gross revenue. The following case is fairly typical of a simple, independent railroad corporation:

It is an independent road 371 miles long, with a capital stock of $1,114,400 and a funded debt of $9,415,000, which is made up of bonds to the amount of $8,555,000 and "equipment trust obli-

gations" to the amount of $860,000. This is evidently a case of a road built chiefly on the proceeds of the bonds, the issue of stock being quite small. The gross revenue for 1901–1902 was $1,708,937. Of this, $1,101,884 or 64.5 per cent was spent in operating expenses. Of the remainder, $552,821 or 32.4 per cent was needed for the "fixed charges". This left only $54,232 available for anything else. Although this amounted to nearly 5 per cent on the rather small issue of capital stock, no dividend was declared. It was evidently preferred to add this amount to their working capital or perhaps to use it in improvements. Such an action is virtually the reinvestment of profits for the improvement of the road.

The complication, due to the corporate ownership of railroad stocks and bonds, as well as other income-bearing property, by railroad corporations, makes it impossible to analyze the financial statements of most railroad companies as easily as has been done above. A disbursement item by one corporation is an income item for another corporation. The Interstate Commerce Commission publishes each year a statement which analyzes the reports of all the roads of the country and considers them as one system, which is done by eliminating all but the net balance of all intercorporate payments. Some of the items of the statement for the year ending June 30, 1912, are as follows:

	(Millions)
Operating revenues (rail operations)	$2,842,
Operating expenses (rail operations)	1,972,
Total net revenue (adding a million from "outside operations")	871,
Taxes accrued	120,
Operating income	751,
Other income (chiefly dividends and interest on stocks and securities owned)	89,
Gross income	840,
Deductions from gross income (chiefly interest on funded debt and net intercorporate balances)	488,
Net corporate income for year	352,
Adding balance of profit and loss, June 30, 1911	1,124,
Gross surplus, June 30, 1912	1,477,
Net loss during year (from "adjustments, through profit and loss")	30,
Surplus available for appropriation	1,447,
Net dividends declared during year $299,	
Appropriations for extensions and betterments $ 53,	352,
Balance, carried to general balance sheet	$1,095,

Although it may appear ultraconservative to have allowed dividends of only 299 millions when the "surplus available for appropriation" was nearly five times that amount, it should also be noted that the net balance carried over was but little over one-half of the annual operating expenses. The balance, after paying interest charges for the year, would not run the roads four months if all income were cut off. While this is an inconceivable contingency, the margin for working capital is none too large. Even this margin was reduced 30 millions during the year.

164. Fixed Charges. The fixed charges of a simple railway corporation which operates only the line which it owns will consist chiefly of the interest on its bonds. Besides this there may be the interest on "equipment trust obligations" which are merely a particular form of bond issued to pay for equipment needed by the road. Another item will be the interest on sundry interest-bearing current liabilities; this is generally but a small percentage of the fixed charges, but the current liabilities are often made to disappear by a new issue of bonds which take up an old issue and at the same time cover all floating liabilities.

The complicated financial relations existing between operating roads and their leased lines introduces some other items which are entered under fixed charges. One of these items, which is always less than 1 per cent of the total fixed charges, is called "salaries and maintenance of organization". These refer to the salaries which are paid to a few of the general officers of a leased road who are retained to continue such work. Another item is placed, when it occurs, among the fixed charges; this is the rental paid for a leased road. As this is an "intercorporate" payment, it did not appear in the above general summary for the roads of the United States, nor did it appear in the detailed statement of the road previously described, since that road had no leased lines.

165. Net Revenue. The net revenue is that which remains after the operating expenses and fixed charges have been paid. In general it is available for dividends, but practically a very considerable proportion of it will be devoted to improvements or to the accumulation of a surplus which will serve as "working capital". During the year 1911–12, 34.57 per cent of railroad stock paid *no* dividends, although the case quoted above is but one of many in

which there was a considerable surplus after paying the operating expenses and fixed charges. Dividends of less than 4 per cent were paid on 2.67 per cent of stock.

This small proportion shows the tendency to pass the dividend unless it may be made larger. About 49 per cent of the stock paid dividends varying from 4 to 8 per cent. This represents the bulk of the stock paying normal dividends. Smaller percentages of the stock paid higher rates. On 8.43 per cent of stock, dividends of 10 per cent and over were paid. Of course this last represents roads which are short and very exceptional in character. It should also be kept in mind that the percentages of dividend-paying stock quoted above are almost the highest of any in the history of railroading. If general railroad conditions should ever return to those existing in 1896, when over 70 per cent of all the stocks paid no dividends, railroad stock would be less attractive for investment than now in spite of the abnormal profits which are occasionally realized.

166. Operating Expenses. *Uniformity per Train-Mile.* The classification of operating expenses here adopted will follow, both in general and in detail, the classification used by the Interstate Commerce Commission. The figures given will, in general, be *averages.* This is further justified by the very remarkable fact that the expenses *per train-mile* are nearly constant, whether the trains be few or many, heavy or light. Of course there are very numerous exceptions to this rule, but it will generally be found that the marked exceptions apply to very short roads which either have abnormal traffic or have peculiar financial relations with a parent company which is operating it.

The report for 1901–2 shows that the ten greatest railroads of the country, each operating more than 4000 miles of road, spent $1.167 per train-mile. The average for the whole United States was $1.1796. It should also be noted that the ratio of total operating expenses to total receipts from operations was 59.78 per cent for the ten roads and 64.66 per cent for the whole United States. To judge of the operating expenses of smaller roads, the figures for No. 10, Table XIV, were taken from the report, the selections being made at random except that the lengths were all less than 100 miles and all of the roads were "operating roads independent".

TABLE XIV

Operating Expenses

No.	Length (miles)	Operating Expenses per Train-Mile	Ratio of Total Operating Expenses to Total Receipts from Operation (per cent)
1	21.25	$0.70621	71.62
2	32.60	0.47828	64.21
3	31.00	0.60649	96.12
4	64.10	0.90588	43.41
5	42.00	0.54323	63.07
6	61.00	0.75357	81.05
7	50.00	0.87456	90.32
8	50.39	2.07044	97.58
9	70.78	1.02854	53.46
10	52.20	1.74952	62.15
Average		$0.97167	72.30
10 longest roads		1.167	59.78
Whole U. S.		1.17960	64.66

A little study of the above figures will show, as might be expected, that local conditions will so affect a very small road that its operating expenses per train-mile may be considerably more or considerably less than the average. The average value for the ten short roads here chosen is less than the average for the United States, and although two of the ten are much greater than the average, it is found that the average value for short roads is a little *less* rather than more.

The reasons for the uniformity are not difficult to understand. Although the gross expense of any one item (such as rail renewals) for a large road is enormously greater than the same item for a small road, the divisor (the number of trains) is correspondingly greater and the quotient, which is the expense for that item per train-mile, is substantially uniform.

Average Cost of a Train-Mile. The increase in the average cost of a train-mile is shown in Table XV, which gives the average cost of operating a train 1 mile during 23 consecutive years. The nearly uniform growth of over 73 per cent between 1895 and 1912 is very significant. While predictions of future cost are necessarily guesswork, estimators in railroad economics must make the best possible predictions for five or ten years ahead. There seems to be no

TABLE XV

Average Cost of Operating a Train 1 Mile

(All roads in U. S.)

Year	Cents	Year	Cents	Year	Cents	Year	Cents
1890	96.006	1896	93.838	1902	117.960	1908	147.340
1891	95.707	1897	92.918	1903	126.604	1909	143.370
1892	96.580	1898	95.635	1904	131.375	1910	148.865
1893	97.272	1899	98.390	1905	132.140	1911	154.338
1894	93.478	1900	107.288	1906	137.060	1912	159.077
1895	91.829	1901	112.292	1907	146.993		

reason to hope for a decrease in the rate or to expect anything else than a continued increase, even though it may prove less rapid than heretofore.

167. Classification of Operating Expenses. In Table XVI is shown the classification adopted by the Interstate Commerce Commission—the total cost for each item, each item's per cent part of the total, and the cost in cents per train-mile, which is found by multiplying each percentage by the average cost per train-mile for that year ($1.59077, or 159.077 cents). While these averages are very instructive in giving a broad view of the subject, they must be used cautiously. For example, the fuel required per mile for locomotives is a very variable quantity, depending on the size of the locomotive and the amount of work done, and it would be very foolish to make any calculations on the basis that the cost of fuel per locomotive-mile would be exactly 16.27 cents.

168. Maintenance of Way and Structures. The cost of ties is the largest single item for track material; the cost per train-mile has nearly doubled since 1895. This has been due to a combination, in varying proportions, of three causes—(a) increased cost of ties; (b) lowering of quality to pass inspection, due to growing scarcity; and (c) increase in train load and concentrated wheel load, resulting in more rapid deterioration. There seems to be no chance of decrease in cost in the future unless possibly by more effective preservative processes or by the invention of a metal or a steel-concrete tie which shall be so durable that, in spite of increased first cost, it is cheaper per train-mile.

The cost of roadway and track (item 6) is the labor of track

TABLE XVI

Analysis of Operating Expenses of all Railroads in the United States for Year Ending June 30, 1912, Showing Percentage of Each Item to Total and Cost in Cents per Train-Mile

Item No.	Account	Total Amount (thousands)	Per Cent of Total Expenses	Cents per Train-Mile
	MAINTENANCE OF WAY AND STRUCTURES			
1	Superintendence	$18,789,	0.990	1.58
2	Ballast	7,157,	0.377	.60
3	Ties	55,463,	2.921	4.65
4	Rails	16,438,	.866	1.38
5	Other track material	17,346,	.914	1.45
6	Roadway and track	129,397,	6.815	10.84
7	Removal of snow, sand, and ice	6,920,	.364	.58
8	Tunnels	1,141,	.060	.10
9	Bridges, trestles, and culverts	27,712,	1.460	2.32
10–12	Crossings, all; fences; snow structures	8,066,	.425	.68
13–15	Signals, telegraph, electrical power transmission	13,681,	.720	1.14
16, 17	Buildings, grounds, docks, wharves	35,389,	1.864	2.96
18	Roadway tools and supplies	4,480,	.236	.38
19	Injuries to persons	1,989,	.105	.17
20, 21	Stationery, printing, and other expenses	1,038,	.054	.09
22, 23	Joint tracks, etc. (net balance)	3,463,	.182	.29
		348,471,	18.353	29.20
	MAINTENANCE OF EQUIPMENT			
24	Superintendence	13,175,	.694	1.10
	Repairs, renewals, and depreciation:			
25–30	Locomotives, steam and electric	175,889,	9.263	14.74
31–33	Cars, passenger	38,968,	2.052	3.26
34–36	Cars, freight	183,968,	9.690	15.41
37–39	Equipment, electrical, car	318,	.017	.03
40–42	Equipment, floating	1,333,	.071	.11
43–45	Equipment, work	6,128,	.322	.51
46	Equipment, shop(machinery and tools)	10,418,	.548	.87
47	Equipment, power plant	268,	.014	.02
48	Injuries to persons	1,818,	.096	.15
49, 50	Stationery, printing, and other expenses	4,036,	.213	.34
51, 52	Joint equipment, at terminals (net balance)	676,	.036	.06
		436,995,	23.016	36.61
	TRAFFIC EXPENSES			
53–60	Agencies; advertising; fast freight lines; etc.	59,047,	3.110	4.95

TABLE XVI (Continued)

Analysis of Operating Expenses of all Railroads in the United States for Year Ending June 30, 1912, Showing Percentage of Each Item to Total and Cost in Cents per Train-Mile

Item No.	Account	Total Amount (thousands)	Per Cent of Total Expenses	Cents per Train-Mile
	TRANSPORTATION EXPENSES			
61, 62	Superintendence and train dispatching	$40,743,	2.146	3.41
63	Station employes	133,877,	7.051	11.22
64–66	Weighing; car service association; coal and ore docks	15,949,	.839	1.33
67–72	Yards (wages, expenses, supplies)	116,781,	6.151	9.79
73–76	Yard locomotives (fuel, water, lubricants, supplies)	33,658,	1.773	2.82
77, 78 104, 105	Operating joint tracks, terminals, yards, and facilities (net balance)	10,430,	.550	.88
79, 80	Motormen and road enginemen	120,966,	6.371	10.14
81	Road locomotives, engine-house expenses	33,951,	1.788	2.84
82	Road locomotives, fuel	194,142,	10.225	16.27
83	Road locomotives, water	12,482,	.657	1.04
84, 85	Road locomotives, lubricants, and other supplies	7,430,	.392	.62
86, 87	Operating power plants, purchased power	1,797,	.095	.15
88	Road trainmen	128,339,	6.759	10.75
89	Train supplies and expenses	34,462,	1.815	2.89
90–92	Interlockers, signals, flagmen, draw-bridges	17,831,	.939	1.49
93	Clearing wrecks	5,167,	.272	.43
94–98	Telegraph, floating equipment, station-ery, miscellaneous	20,009,	1.054	1.68
99–103	Loss and damage to property, personal injuries	56,838,	2.994	4.76
		984,852,	51.871	82.51
	GENERAL EXPENSES			
106–116	Salaries of general officers, clerks, etc.; law, insurance, pensions, miscella-neous	69,297,	3.650	5.81
	Total Operating Expenses	$1,898,662,	100.000	159.08

maintenance. The average daily wages of trackmen have increased almost uniformly from $1.22 in 1900 to $1.50 in 1912; the wages of section foremen are quite uniformly about 30 per cent above those of trackmen. The number of trackmen per 100 miles of line has also increased from 118 to 143 in this same period, but there have

been greater fluctuations. The increased number and increased wages have combined to increase very greatly the cost of track maintenance.

169. Maintenance of Equipment. The cost of this group of items has been increasing very greatly in recent years, not only in gross amount but also in percentage to total cost of a train-mile and in cents per train-mile. This increased cost is due to higher labor costs in the shops and higher costs for materials. While a change of alinement, involving increase or decrease in length of road, or "distance", will affect these items, the cost is not directly proportional to distance and the same remark applies to many other items. Curvature affects the cost of repairing very greatly—chiefly in wheel wear, and the engineer must consider this in estimating the value of a saving in curvature. The rate of grade also has an effect on this item.

During the first years of the life of a locomotive, the repairs (barring accidents) will be small, but as the locomotive grows older they increase in a growing ratio. When the annual repair charge becomes one-fourth (or in exceptional cases one-third) of its first cost, the locomotive should be sent to the scrap pile, for in such cases the cost per train-mile becomes larger than a reasonable annual charge, allowing for all depreciation, on the cost of a new locomotive. When an old locomotive is replaced by one of a better and more costly type, the *excess* cost should be charged to "betterments", or "permanent additions to equipment".

170. Transportation Expenses. There are five items in this group which amount to more than 5 cents per train-mile. The largest is that for fuel. The cost of this (for both yard and road locomotives) has nearly doubled since 1895. This is due partly to increase in cost of coal per ton and partly to the great increase in the power of the average locomotive and therefore in the amount of coal burned per mile. The other four of the five large items are made up almost exclusively of wages, which have increased very greatly in the past twenty years. Any economic calculation, which requires a prediction of the future cost of operation, must include the probability that the cost of conducting transportation will probably not decrease and may increase very materially even during the next five or ten years.

ECONOMIC LOCATION

171. General Principles Involved. A hasty mental review of the previous discussion, as well as a few considerations of common sense, will show the truth of the following statements:

(1) Disregarding the comparatively rare cases in this country where a practicable location of any kind is a creditable engineering feat, it may be said that a comparatively low order of engineering talent will suffice to lay out a line along any general route over which it is physically possible to run trains, and that there are usually several such possible routes. The route selected may not be favorably located for obtaining business, its alinement may be such that its operating expenses are high, and the ruling grades may be so high that only light trains can be run, but the road *can* be operated even with these handicaps.

(2) Among the many possible routes which may be selected for a road, there is one which is superior to any other from an operating or business standpoint, and it is the province and test of the engineer to select that best route.

(3) There are several more or less conflicting interests which must be studied—(a) the maximum of business must be obtained, but this is sometimes only obtainable at great initial cost; (b) the ruling grades must be made as low as possible, which is generally costly, and it *may* require a location which will sacrifice some business; (c) the alinement must be kept easy so as to reduce operating expenses, but this usually is very costly; (d) the total cost must be kept within a figure which will be justified by the future earnings and also leave enough margin as working capital out of the total funds which are raised, so that the road may continue to operate during the five or ten years which are required to build up the "normal" traffic.

(4) Each new route suggested forms a new combination of the above conflicting elements, and the business of the engineer is to estimate and compare these elements, selecting the combination which will give the largest return for the least outlay, considering both initial cost and future operating expenses as elements of the outlay.

172. Reliability and Value of Economic Calculations. The student should not form the idea that the following calculations

will enable one to compute with mathematical precision the effect of changes of alinement. There are far too many elements involved, and the effect of certain influences is variable. But although a precise solution is unobtainable, a solution which is sufficiently accurate for practical purposes may be made, and this is infinitely better than no solution at all. For example, suppose that a very crooked stretch of road may be changed to comparatively easy alinement which saves considerable curvature by an additional expenditure of say $20,000. Assume that it has been computed (by methods developed later) that the operating expenses would be reduced $3500 per year by the reduction of that curvature. As $3500 per year, capitalized at 5 per cent, is equivalent to an investment of $70,000, and as the improvement may be made for $20,000, the improvement is evidently justifiable. Such is the bare outline of the method.

The estimate of the cost of the improvement may be accurately made, but it is not claimed that the estimate of the saving per year is precise. It may, however, be shown that, even with ample allowances for the uncertain items, it is practicable to assign upper and lower limits between which the truth must lie. A greater knowledge of the subject and greater experience on the part of the engineer will enable him to narrow those limits so that the error is immaterial. And frequently even this is unnecessary. The real question is not whether the capitalized value of the improvement is $70,000, or $50,000, or $90,000. It may be that an improvement which would make possible that saving may be made for a few thousand dollars, or it might require $200,000. In either case, the true answer is unquestionable.

If the cost of the improvement is very nearly equal to its computed capitalized value, then no great harm can come from either decision, for the decision would then be based on the willingness of the company to spend additional money. The method furnishes a criterion, which even in the hands of an inexperienced engineer has some value, and which alone gives value to his opinion. But the method enables the experienced engineer to give the best opinion which is obtainable, for it enables him to apply his experience to a method of computation which approaches accuracy as nearly as may be.

It must not be supposed that the numerical values worked out in the following pages are necessarily applicable to any assumed case. They are given to show the *method* of their derivation, and should be modified to fit local conditions according to the best judgment of the engineer.

DISTANCE

173. Relation of Distance to Rates and Expenses. Rates are usually based on distance traveled on the apparent assumption that the value of the service rendered and the cost to the company are directly proportional to the number of miles traveled. The assumption in either connection is not true. If a passenger or a load of freight is to be transported from one city to another city 100 miles away, the service rendered is to accomplish the transfer as easily and quickly as possible. If another road were constructed, perhaps at extravagant cost, by which the distance were cut down to 90 miles, that road would render a greater and better service, because it would reduce the necessary travel, and yet on the mileage basis the shorter road would be entitled to less than the other in spite of the fact that it renders a better service.

The assumption that the cost is proportional to the distance is more nearly correct, although, as will be shown later, even this is far from accurate. It is not difficult to compute an average cost for a large number of passenger trains and, by dividing it by the total passenger mileage, to obtain a value of the cost of a "passenger-mile". But the additional cost of transporting one additional passenger on a regular train is hardly more than the cost of printing his ticket. Even if it were practicable to compute the extra consumption of coal and the infinitesimal addition to other operating expenses due to his being on the train, the added cost would evidently be but an insignificant fraction of the average cost of a passenger-train-mile. The same argument holds, but not to the same extent, if we consider the additional cost of an extra ton of freight.

By the same line of argument it will be shown that a change in distance will not affect the cost of running trains in proportion to the change. It is easy to see that general expenses will be absolutely unaffected by an alteration of alinement which saves a mile

in distance, and it will be shown that even the consumption of fuel does not vary in proportion to the distance. If it were practicable to construct a tariff of rates which should consider excessive curvature and grades on the various parts of the line and make the rates dependent on them as well as on many other constructive features which add to the cost of operation, the rates would be more nearly proportional to the cost, but the public would not appreciate it and it would be useless work. And when it is further shown that it is sometimes justifiable for a road to haul competitive business at a rate actually less than the average cost of their traffic, it will be seen that the relation of distance to rates and expenses cannot be expressed by any simple proportion.

174. Effect on Receipts. Among all the details of alinement, distance is the one for which there is some compensation in an increase, and that is because rates are based on distance rather than on curvature or grades. Although it is unquestionably contrary to public policy to burden traffic unnecessarily by an increase in distance, yet it may be demonstrated that the added receipts from non-competitive traffic due to such increased distance will amount to more than their added cost. But in order to study this feature properly the distinction between competitive and non-competitive rates must be noted. For our purposes traffic may be classified as "through" and as "local", in which through traffic refers to that which passes over *two or more roads*, no matter how long or short any section of the trip may be, and in which local traffic refers to that which is confined to *one railroad system*, though it may run from one end to the other. Further subdivision is necessary as follows:

(1) *Non-competitive local*—on one road with no choice of routes.

(2) *Non-competitive through*—on two (or more) roads but with no choice.

(3) *Competitive local*—a choice of two or more routes, but the entire run may be made on the home road.

(4) *Competitive through*—direct competition between two or more routes, each passing over two or more lines.

(5) *Semi-competitive through*—a non-competitive haul on the home road and a competitive haul on foreign roads.

Receipts for traffic passing over two or more lines are divided between the lines in proportion to mileage. "Terminal charges" are sometimes subtracted from the amount before the division is made and sometimes a strong road forces a weaker road to submit to some other exaction before the division is made, but the final division is made in proportion to the mileage for each passenger ticket or each freight bill. It may be shown that the cost of operating an additional mile is about 58 per cent of the average cost. This means that on all non-competitive business (class 1) there is an actual profit in this added distance. On the other hand, competitive rates are made with small regard to distance, are generally equal, and therefore any added distance results in a sheer loss without any compensation. This applies to all the traffic of class 3.

Illustrative Example. The other classes of traffic are affected by distance in various degrees between these two extremes. Suppose that the distance on the home road for any given shipment is 100 miles, and the distance on the foreign road for that shipment is 150 miles; suppose that the freight charge is \$10; then the home road will receive $\frac{100}{100+150}\times\$10=\$4.00$. This means 4 cents per mile for that particular class and weight of freight. Suppose that the distance is increased 5 miles on the home road, but assume that the traffic is wholly competitive and therefore that the total rate received will be \$10, regardless of the added distance. Then the home road will receive $\frac{105}{105+150}\times\$10=\$4.1176$. If we allow to the original 100 miles its full previous allowance of 4 cents per mile, we have left 11.76 cents to pay for the extra 5 miles. This is at the rate of 2.352 cents per mile, which is 58.8 per cent of the 4-cent rate.

This nearly equals the computed percentage of added cost for additional distance computed in miles. Therefore, if the original 4-cent rate is profitable, the added receipts due to the added distance will be sufficient to operate the added distance profitably, or without loss. Incidentally, the foreign road suffers, for it will receive less for precisely the same service. The above numerical case is very nearly at the dividing line between profitable and unprofitable addition to distance. If the length of the home road

is but a small proportion of the total distance, then it may be similarly computed that an addition to distance is distinctly profitable. On the other hand, if the length of the home road is a large proportion of the total distance, an addition to distance is distinctly unprofitable, and when the length of the foreign road is zero (which means that the competitive haul is entirely on the home road) then any addition to distance is sheer loss without any compensation, even partial.

The above numerical case represents but one of an almost infinite number. Each station along the line has possible traffic connection with almost every other railroad station in the country. The route from each station to every other station represents a new combination, and the net effect of the added distance is the combined effect of all the separate cases. This instantly shows that a precise mathematical solution is impossible, but the above solution has value in pointing out some general truths as follows:

In *all* non-competitive business, whether through or local, the added receipts due to added distance will be profitable, and if the business of a road is almost entirely non-competitive there is little or no disadvantage in added distance, especially if the construction is cheapened in spite of the added distance. For example, a road which follows the banks of a very crooked river may cost less to build, even though much longer and more crooked, than the road which tunnels through the horseshoe bends.

When roads handle a very large amount of competitive business any additional distance may be a source of loss on that class of business, and the loss may be so serious as to justify a considerable expenditure to reduce it. Another reason for the subsequent expenditure of money to reduce distance is that, after freight rates are once established between roads on through business, they are not apt to be disturbed to make them conform to the slight fluctuations of distance caused by changes in the alinement.

The above statements can be reduced to the general conclusion that since every road handles a considerable proportion of non-competitive business, there is always some compensation for the added expenses of operating additional distance. The majority of small roads do a business which is almost wholly non-competitive, and to them the added receipts will usually pay for the added dis-

tance, even if it is not an actual source of profit. Finally, it may be said that a road is not usually justified in making an additional expenditure to shorten distance (i.e., adopt a route which will have a greater gross cost in spite of the shortened distance) unless it handles a very large amount of highly competitive business.

There are some other considerations which must not be ignored in considering this question. One of them is the question of the additional time required to make the trip. This may be important in two ways. (1) The competition for passenger business between two cities, such as New York and Philadelphia, or Philadelphia and Atlantic City, might be so keen that a difference in length of line which would affect the running time by even 10 minutes would have great financial importance. (2) A very considerable change in distance may have a serious effect on the operation of the heavy through-freight trains, although it would not ordinarily increase the total cost of operating those trains over that division more than the extra number of train-miles times the reduced train-mile cost. But in any case, this phase of the question should not be ignored.

Another consideration is the possible effect on the business done. "A short straight line" is the popular description of a well-designed road. If the engineer's aim for a *short* road leads him to pass by sources of income and thus lose them, his road will have little business and the receipts will be reduced because it is short. As a general rule "adopt that route which will give the greatest traffic per mile of road". On the one hand, this avoids the error of running a line which is excessively crooked in the effort to secure every possible element of traffic and thus burdening the whole traffic with an excessive haul, and on the other hand, avoids running a line which misses important sources of traffic in the effort to have a straight line.

CURVATURE

175. Operating Disadvantages of Curvature. The non-technical mind appreciates, even too readily, the disadvantages of curvature. But it is generally true that the ones which are most thoroughly appreciated by the public are of least economic value to the engineer. The several disadvantages will be classified

and discussed in an order which is perhaps the inverse order of their importance, as follows:

(1) It increases the danger of collision and derailment and aggravates the damages of a derailment when it occurs. The application to be made to this statement of undoubted fact is—how much is a road justified in expending in order to reduce or eliminate any given curve? Since the entire elimination of curves is a physical as well as a financial impossibility, the question reduces to the lessening of danger from accidents that would result from such reductions as are possible. The Interstate Commerce Commission report on railroad accidents for the year ending June 30, 1902, showed that the number of passengers carried 1 mile for one killed was 57,022,283. This means that the chances are even that a passenger could ride 57,000,000 miles before he would be killed. If he were to ride continuously at the rate of 60 miles per hour, it would require over 9,500,000 hours, or nearly 400,000 days, which is considerably over 1000 years.

But how many of such casualties are due to curvature, and how many million miles must be traveled by the average passenger before, according to the law of probabilities, he would be killed by an accident which should not only be directly charged to curvature, but also to curvature which is physically or financially avoidable. If we estimate the number of curves on all the railroads of the country as 250,000, what is the probability of a fatal accident happening on any one curve and how much may be spent on that curve to reduce the danger? Even if it were spent, would there remain *no* danger of an accident there? A thorough logical analysis of this question shows that although it is always proper to take reasonable precautions to avoid accident at an especially dangerous curve (such as maintaining a flagman there), it is impossible to assign any financial value to the mere *danger* of accident which would accomplish anything toward modifying construction.

(2) Curvature may affect traffic (a) by reducing the possible speed of fast trains. There is some force to this objection as it applies to sharply competitive traffic between two cities—a traffic of which most roads have not a trace. The extent to which the passenger traffic might be increased by the minute or two which might be saved is, however, so uncertain that it defies analysis.

(b) It may produce rough riding, and (c) it may create an apprehension of danger which may of itself deter travel. The disadvantages resulting from all three of these sub-causes are greatly reduced by good roadbeds and transition curves. Freight traffic, which comprises about two-thirds of the total, is unaffected by it unless the curvature is extreme, and the passenger traffic of most roads will not be influenced by it; and therefore an engineer is not ordinarily justified in giving it any financial weight.

(3) It *may* affect the operation of trains (a) by limiting their length and (b) by limiting the type and weight of engines. There are a few instances known where roads which run along a river bank have very easy ruling grades and on which the curvature is perhaps very sharp on account of sharp bends in the river. On such roads the curvature may be the feature which limits the length of trains, but such cases are rare and even when they occur a computation similar to that later developed will show how much may profitably be spent to reduce the rate of curvature. If a long grade up a mountain were kept uniform, regardless of curves, the curves would add such resistance that they would limit the length of trains, but good practice requires that the grades shall be "compensated for curvature", as explained later.

The excessively sharp curvature which has been used on some mountain roads may preclude the use of some of the largest types of locomotives. But such roads ordinarily do not have a traffic which justifies the use of the heaviest locomotives. And when it is considered that a Mallet locomotive, having sixteen drivers and a weight on the drivers of over 400,000 pounds, can be operated on a 20-degree curve, any limitation in the use of engines may be ignored for all ordinary railroad work.

(4) Curvature increases operating expenses. This disadvantage is definite, positive, and approximately computable, and since a reduction in expenses may be made by reducing curvature, we must calculate the effect of curvature on operating expenses.

176. Compensation for Curvature. Curvature makes a very definite increase in train resistance, and such increased resistance is readily equated to its equivalent in added grade. Assuming that the curve resistance on a 6-degree curve is 4 pounds per ton, which is the grade resistance of a 0.2-per-cent grade, if there should be

a 6-degree curve on a 1.0-per-cent grade, the resistance on that grade would be the same as on a straight track having a 1.2-per-cent grade. On this basis, if 1.2 per cent were selected as the ruling grade and it became necessary to introduce a 6-degree curve, the grade should be reduced on that curve to 1 per cent so that the total resistance on that curve shall be no greater than on the tangent. This is the fundamental idea of curve compensation. On grades which are so low that they will never be ruling grades even if the rate of ruling grade is reduced by reconstruction, there is no necessity for curve compensation, but the neglect of it on ruling grades means that the ruling grade is practically increased to the grade which is the equivalent of the combined grade and curve resistance.

Rate of Compensation. This term means such a reduction in the grade that the saving in grade resistance equals the curve resistance. But curve resistance varies somewhat as the velocity, the condition of the rails, and even the type of the wheel base. For simplicity of calculation the curve resistance is usually assumed to vary as the degree of curvature. While this is nearly true for low degrees of curvature, it becomes grossly inaccurate for excessively sharp curvature, on which the resistance is fortunately much less than its proportionate amount. This is probably due to the fact that a large part of the resistance from curvature is due to causes which are independent of the degree of curve. The resistance will amount to about 2 pounds per ton per degree of curve (equivalent to a 0.1-per-cent grade) when the velocity is very low—as when starting a train. It is less for fast trains than for slow trains, but considering that it is the slow and heavy freight trains which must be chiefly considered, the larger values for compensation which are needed for the slower velocities must be used. Compensation results in a loss of elevation for a given horizontal distance and when money has been spent in "development" in order to reduce the grade to some desired limit, any useless compensation is a waste and should be avoided. If a curve occurs on a grade immediately below a stopping place for *all* trains (or at least all trains which are so heavy that they will be affected by the ruling grade), the compensation may be reduced or omitted altogether on the ground that the curve resistance would simply use up the energy which might otherwise be used up by brakes in stopping the train. If

that heavy grade should continue on above that stopping place, then the compensation should be made even greater than the average to allow for the increased resistance while starting. Since the curve resistance merely adds to the virtual grade, and the object of compensation is to prevent such additions from increasing the ruling grade, there is no object in using compensation on a grade, which is already so low that the added resistance will not make it virtually equal to the ruling grade. An exception to this lies in the danger that it may some time prove desirable to make such changes of alinement that the ruling grade is very materially cut down, and it might happen that neglect to compensate would add that much to the revised ruling grade. The above discussion may therefore be reduced to the following rules:

(1) On the upper side of a stopping place for all heavy trains compensate 0.10 per cent per degree of curve.

(2) On the lower side of such a stopping place do not compensate at all—but this rule should be applied cautiously.

(3) Ordinarily compensate about 0.035 per cent per degree of curve.

(4) Increase this rate to 0.04 per cent when the curve is habitually operated at slow speed, or when the super-elevation is excessive for freight trains, unless it is found that the higher rate of compensation causes such a loss of height that the grade on the tangent must be increased.

(5) Curves which are so much less than the ruling grade, that they will *always* be minor grades need not be compensated, but the possibilities of a future reduction in the rate of ruling grade should be considered.

177. Limitations of Curvature. Surveys for railroads are frequently made under instructions that curves (and also grades) shall not exceed some chosen limitations. What should be the limitation, if any, of the degree of curvature? Probably no definite answer is correct unless it be said that there should be no limitation. It has been shown that all ordinary degrees of curvature even up to 20 degrees will still permit the use of heavy engines, and there are numerous instances where a heavy railroad traffic has been hauled for many years around excessively sharp curves without any serious difficulty—as, for instance, the traffic on the Baltimore & Ohio

Railroad at Harper's Ferry, which for many years was hauled around a 19-degree 10-minute curve (radius 300 feet). This curve was changed some years ago. Of course the young engineer should not conclude from this that curvature is of no consequence, and that he may recklessly put in as much and as sharp curvature as might seem at first the easiest plan to adopt. It may be shown that there is a definite money value in reducing every possible degree of central angle and also that the radius of curvature should be made as large as possible without a serious sacrifice of other interests or extravagant expenditure. It generally happens, when running a road through a mountainous country, and when a high summit must be crossed, that the grades can only be reduced by the adoption of very sharp curvature or by a large expenditure in construction. Since the expenditure is usually limited by financial considerations, the error of adopting a high ruling grade is usually made and the degree of curvature is limited to a low figure which is ridiculously out of proportion to the general condition of the road.

Sometimes the limited money at the disposal of the company is wasted on a route which gives easy curves when the money could have been spent advantageously in other ways. The most common error is the needless increase in the ruling grade. Many railroads have been laid out under the instructions that the maximum grade may be 60 feet per mile and the minimum curve 6 degrees. These limits have been used separately, or in combination, with the result that when a 6-degree curve occurred on a 60-foot grade, the virtual grade was thereby increased (on a 0.035-per-cent basis) to over 71 feet per mile. While a grade of 60 feet per mile might be a very proper ruling grade under certain conditions, it might readily happen that the option of using a 10-degree curve (properly compensated) would permit adopting a line with a ruling grade so much less than 60 feet that the advantages of the reduction of grade would far outweigh the comparatively insignificant disadvantages of the sharp curvature. Therefore, as a general answer it may be said that the limits, if any, should conform to the general character of the country, and that when it appears possible to obtain a great advantage, such as the reduction of the ruling grade, by an increase in the degree of curvature and even in the degrees of central angle, such increase should be made unless it may be definitely computed

that the disadvantages of the increased curvature would outweigh the advantages of the reduced grade.

GRADE

178. Distinction between Minor and Ruling Grades. The distinction between minor and ruling grades must be very clearly understood before their operating disadvantages may be computed. The cost of running a train one mile is largely independent of whether the train is long or short, heavy or light. The receipts for transporting so many tons of freight is a definite quantity and is unaffected whether it is transported in one train load or two. If it is possible by a reduction in grade to haul in a single train load as much freight as would require two train loads by the old plan, then, since the receipts are constant and the cost of the two light trains will be nearly double that of the one heavy train, it is evident that the low-grade plan will be very profitable and the other plan correspondingly costly and financially ruinous.

Although it is not often practicable to double the weight of the train behind a freight engine, a very material increase in the train load can generally be made by such reduction of the ruling grade as is practicable, and such increase in train load frequently makes all the difference between large dividends and an actual deficit. The ruling grade definitely limits the load that can be hauled by an engine with a given weight on the drivers and its financial effect is very great. On the other hand, a minor grade does not limit the number of cars and its effect on operating expenses is confined chiefly to an increase in the consumption of fuel and other locomotive supplies. While this increase in expense has an importance which is worth computing, it is insignificant compared with the cost of running additional trains to handle a given traffic.

The real cost of minor grades is also less than it might otherwise be considered owing to the fact that each rise has its corresponding fall. Even though several high summits may be crossed, the difference in elevation of the terminals, say 200 feet, or even 500 feet, is insignificant from the standpoint of grade when the distance is perhaps as many miles. And even in the extreme case when the grade is all in one direction, the additional energy required to climb the grades is partly returned in the assistance the grade

gives to trains on the return trip and the consequent saving in motive power.

179. Laws of Accelerated Motion. *Application to Movement of Trains.* When a train starts from rest and acquires its normal velocity, say 30 miles per hour, the engine must develop not only the power required for all the ordinary tangent and perhaps curve and grade resistances, but also the "kinetic energy" corresponding to the velocity which has been acquired. This kinetic energy is not wasted; all of it is transformed back into work of some kind. The energy may be consumed and wasted in the brakes, but it may also be spent (and is so spent) in overcoming resistances whenever the velocity of the train is reduced. The amount of this kinetic energy is a definite mathematical quantity. The laws of Mechanics tell us that this energy equals $W\ (v^2 \div 2g)$, in which W is the weight of the train, v is its velocity in feet per second, and g is the acceleration of the force of gravity, which equals 32.16 feet per second in a second.

A better appreciation of this force may be obtained by considering for a moment that if the train could move along the track without any resistance, then, when running at a velocity of v feet per second, it possesses a kinetic energy which would raise it to a height of h feet, where $h = v^2 \div 2g$. If we consider that the engine is furnishing exactly the power required to overcome the tractive resistances, then the train would run until it had climbed a grade to a height of h feet, no matter whether it was accomplished in 100 feet, or a mile. By an expansion of the theory it is also shown that when the train has climbed a vertical height of h' feet (less than h), it will have left a velocity $v' = \sqrt{2g\ (h - h')}$.

Illustrative Example. Assume that the velocity of a train is 30 miles per hour, or 44 feet per second. It then has a kinetic energy which would raise it a height $h = \frac{44^2}{2 \times 32.16} = 30.1$ feet. If the engine furnished just enough energy to overcome the tractive resistances, the kinetic energy would carry the train up a grade of 15 feet per mile for a distance of about 2 miles, or up a grade of 60 feet per mile for a distance of about $\frac{1}{2}$ mile. If the train were moving up a grade of 20 feet per mile and had proceeded half a mile, it would have climbed 10 feet and would still have a kinetic

energy corresponding to 20.1 feet, and its velocity would then be $v' = \sqrt{2 \times 32.16 \times 20.1} = 35.9$ feet per second, or 24.5 miles per hour.

If the train were a solid mass the above figures would be absolutely correct, but the solution is a little complicated by the fact that an appreciable part of the weight of the train consists of revolving wheels, to which must be imparted the kinetic energy of rotation, in addition to the kinetic energy of translation. The ratio of this rotative kinetic energy to that of translation depends chiefly on the ratio of the weights of the wheels and of the whole car or engine. Evidently this ratio depends on the detailed design of the rolling stock, and more especially on whether the cars are loaded or empty. This consideration shows that no one value will be accurate for all cases, but there will be little error in adopting 5 per cent as an average value for the increase in the kinetic energy.

Table XVII, which will be found very useful in these computations, has therefore been compiled on the following basis:

$$\text{"Velocity head"} = \frac{v^2 \text{ in ft. per sec.}}{2 \times 32.16} = \frac{1.4667\ V^2 \text{ in m. per h.}}{64.32}$$

$$= 0.03344 V^2$$

and, adding 5 per cent for rotative kinetic energy of the wheels, $= 0.00167 V^2$

Therefore, corrected velocity head $= 0.03511 V^2$

Part of the figures of Table XVII were obtained by interpolation, and, therefore, there may be an error of a single unit in the hundredths place in some of the figures, but considering the uncertainties in the problem, the exact value to hundredths is of no practical importance. Examples of the application of this table will be given later.

The tractive force required to produce this acceleration in a given distance may be stated as

$$P = \frac{W}{2gs}(v_2^2 - v_1^2)$$

in which v_1 and v_2 are the lower and higher velocities in feet per second, s is the distance in feet, g is the acceleration of gravity (32.16), and W is the weight in pounds. If we substitute $W = 2000$ (or one ton), $g = 32.16$, $v_1 = V_1 \frac{5280}{3600}$, and $v_2 = V_2 \frac{5280}{3600}$, to reduce the

TABLE XVII

Velocity Head (Proportional to Kinetic Energy) of Trains Moving at Various Velocities

Velocity (miles per hour) V	Velocity Head $V^2 \times 0.03511$									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
5	0.88	0.91	0.95	0.99	1.02	1.06	1.10	1.14	1.18	1.22
6	1.26	1.31	1.35	1.40	1.44	1.48	1.53	1.58	1.62	1.67
7	1.72	1.77	1.82	1.87	1.92	1.97	2.03	2.08	2.14	2.19
8	2.25	2.30	2.36	2.42	2.48	2.54	2.60	2.66	2.72	2.78
9	2.85	2.91	2.97	3.04	3.10	3.17	3.24	3.30	3.37	3.44
10	3.51	3.58	3.65	3.72	3.79	3.87	3.95	4.02	4.10	4.17
11	4.25	4.33	4.41	4.49	4.57	4.65	4.73	4.81	4.89	4.97
12	5.06	5.15	5.23	5.32	5.41	5.50	5.58	5.67	5.75	5.84
13	5.93	6.02	6.12	6.21	6.31	6.40	6.50	6.59	6.69	6.78
14	6.88	6.98	7.08	7.19	7.29	7.39	7.49	7.60	7.70	7.80
15	7.90	8.00	8.11	8.22	8.33	8.44	8.55	8.66	8.77	8.88
16	8.99	9.10	9.21	9.32	9.43	9.55	9.67	9.79	9.91	10.03
17	10.15	10.27	10.39	10.51	10.63	10.75	10.87	10.99	11.12	11.25
18	11.38	11.50	11.63	11.76	11.89	12.02	12.15	12.28	12.41	12.55
19	12.68	12.81	12.95	13.08	13.22	13.35	13.49	13.63	13.77	13.91
20	14.05	14.19	14.33	14.47	14.61	14.75	14.89	15.04	15.19	15.34
21	15.49	15.64	15.79	15.94	16.09	16.24	16.39	16.54	16.69	16.84
22	17.00	17.15	17.30	17.46	17.62	17.78	17.94	18.10	18.26	18.42
23	18.58	18.74	18.90	19.06	19.22	19.38	19.55	19.72	19.89	20.06
24	20.23	20.40	20.57	20.74	20.91	21.08	21.25	21.42	21.59	21.77
25	21.95	22.12	22.30	22.48	22.66	22.84	23.02	23.20	23.38	23.56
26	23.74	23.92	24.10	24.28	24.46	24.65	24.84	25.03	25.22	25.41
27	25.60	25.79	25.98	26.17	26.36	26.55	26.74	26.93	27.13	27.33
28	27.53	27.73	27.93	28.13	28.33	28.53	28.73	28.93	29.13	29.33
29	29.53	29.73	29.93	30.13	30.34	30.55	30.76	30.97	31.18	31.39
30	31.60	31.81	32.02	32.23	32.44	32.65	32.86	33.08	33.30	33.52
31	33.74	33.96	34.18	34.40	34.62	34.84	35.06	35.28	35.50	35.72
32	35.95	36.17	36.39	36.62	36.85	37.08	37.31	37.54	37.77	38.00
33	38.23	38.46	38.69	38.92	39.15	39.38	39.62	39.86	40.10	40.34
34	40.58	40.82	41.06	41.30	41.54	41.78	42.02	42.26	42.51	42.76
35	43.01	43.26	43.51	43.76	44.01	44.26	44.51	44.76	45.01	45.26
36	45.51	45.76	46.01	46.26	46.52	46.78	47.04	47.30	47.56	47.82
37	48.08	48.34	48.60	48.86	49.12	49.38	49.64	49.91	50.18	50.45
38	50.72	50.99	51.26	51.53	51.80	52.07	52.34	52.61	52.88	53.15
39	53.42	53.69	53.96	54.23	54.51	54.79	55.07	55.35	55.63	55.91
40	56.19	56.47	56.75	57.03	57.31	57.59	57.87	58.16	58.45	58.74
41	59.03	59.32	59.61	59.90	60.19	60.48	60.77	61.06	61.35	61.64
42	61.94	62.23	62.52	62.82	63.12	63.42	63.72	64.02	64.32	64.62
43	64.92	65.22	65.52	65.82	66.12	66.43	66.74	67.05	67.36	67.67
44	67.98	68.29	68.60	68.91	69.22	69.53	69.84	70.15	70.46	70.78

velocities v_1 and v_2 (which are in feet per second) to V_1 and V_2, the velocities in miles per hour, the equation becomes

$$P=\frac{2000}{2\times 32.16s}\left(\frac{5280}{3600}\right)^2(V_2^2-V_1^2)=\frac{66.89}{s}(V_2^2-V_1^2)$$

Adding 5 per cent for the kinetic energy of rotation, the coefficient 66.89 becomes 70.23, but, considering that the 5 per cent correction is somewhat approximate and variable, the coefficient is taken at the even figure of 70 and the equation becomes

$$P=\frac{70}{s}(V_2^2-V_1^2) \qquad (104)$$

in which P is the force in pounds per ton to accelerate a train from a velocity of V_1 miles per hour to V_2 miles per hour in a distance of s feet. Conversely, P is the force in pounds per ton which can be utilized in overcoming tractive or grade resistance when the velocity is reduced from V_2 m.p.h. to V_1 m.p.h. in a distance of s feet.

180. Virtual Profile. The following demonstrations are made on the basis that the ordinary tractive resistances and also the tractive force of the locomotive are independent of velocity. Neither of these assumptions is strictly true, especially the latter. The variation of tractive power with velocity will be considered later (article 191). But the approximate results obtained on the basis of these two assumptions are so instructive and useful that the demonstration is given. Assume that Fig. 157 shows the profile of a section of road and that the grade of $A\,E$ is 0.40 per cent, which is 21.12 feet per mile. Assume also that a freight engine which is climbing up the grade has been so loaded that when the engine is working *uniformly* at its normal maximum the velocity up such a grade would be uniformly 20 miles per hour. But since the train is moving at 20 miles per hour it has a kinetic energy corresponding to a velocity of 14.05 feet (see Table XVII). At A it encounters a downgrade of 0.20 per cent, which is 1500 feet long. Although $A\,B$ has a downgrade of only 0.2 per cent, its grade with respect to the upgrade of $A\,E$ (0.40 per cent) is 0.60 per cent. Therefore B is 9.00 feet below B'. Since the work done by the engine would have carried the train up to the point B' with a velocity of 20 miles per hour, the *virtual* drop of 9 feet will increase the

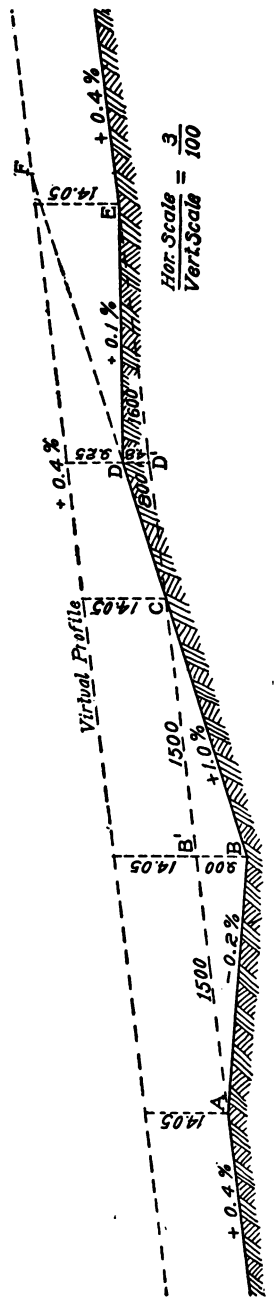

Fig. 157. Typical Profile of Road Section

velocity head from 14.05 feet to 23.05 feet, which corresponds to the velocity of 25.6 miles per hour, and this will actually be the velocity of the train at the point B. At B the grade changes to a 1.0-per-cent upgrade for a distance of 2300 feet.

The approach of the grade $B\ C$ to the grade $B'\ C$ is at the rate of $1.0-0.4$, or 0.6 per cent and therefore the point C will be reached in 1500 feet. In the remaining 800 feet the line will climb to D, which is 4.8 feet above D'. Although at B the train is moving at the rate of 25.6 miles per hour and the engine is working at such a rate that it will carry the train up a 0.4-per-cent grade, yet when climbing up a 1.0-per-cent grade it consumes its kinetic energy in overcoming the additional grade. When it reaches C, it has lost the additional kinetic energy which it gained from A to B, and as it continues it loses even more. When it reaches D, it has lost 4.8 feet more and its velocity head is reduced to $14.05-4.8=9.25$ feet, which corresponds to a velocity of 16.2 miles per hour. At D the grade changes to $+0.1$ per cent.

Here we have the rather surprising condition that, although the grade is actually rising, it is virtually a downgrade under the given conditions, for the engine is working harder than is required to run up merely a 0.1-per-cent grade and hence will gain in velocity. At E, a distance of 1600 feet from D, it reaches what would have been a uniform 0.4-per-

cent grade from A to E and the grade continues at that rate. Although the train has actually climbed 1.6 feet from D to E, it has virtually fallen the 4.8 feet between D and D', and the velocity head has increased from its value of 9.25 feet at D to 14.05 feet, and its velocity is again 20 miles per hour. The upper line represents the "virtual profile", which may always be drawn by measuring off to the proper scale at every point an ordinate which is the velocity head at that point. Since the engine is working uniformly, the virtual profile is in this case a straight line.

Although the variation of resistance and tractive effort with velocity will have some effect on the precision of the above figures, as discussed later, yet the demonstration must not be considered as fanciful and impractical. *Under the given conditions* it is substantially what would take place. If the grade $B\ D$ were continued to F, or until the actual grade intersected the virtual profile, the train would become stalled, for when the engine is loaded for an indefinite haul up a 0.4-per-cent grade, it cannot haul a train indefinitely up a higher grade. Practically the train would stall somewhat short of F, since the tractive resistance increases as the velocity drops to nearly zero. Under such conditions, $B\ D$ is a "momentum grade", which *may be* higher than the ruling grade, and yet it is practically harmless under these conditions, *provided* that a train is never required to stop on that grade. $A\ B\ C$ is technically a "sag" in the grade $A\ C$ and would be considered such even if $A\ B$ were an upgrade (although less than the grade $A\ C$). Such a sag is usually harmless unless it is so deep that the train would acquire a dangerously high velocity at the bottom of the sag B.

In the above numerical case the velocity is only 25.6 miles per hour, which is not at all dangerous even for freight trains in these days of air brakes and automatic couplers. But a much deeper sag might require the use of brakes, which not only consumes some of the energy stored in the train, but also wears out the wheel treads and brake shoes.

Another phase of the question is developed when we consider the action of a train stopping on a grade. Assume, as in Fig. 158, that a train is climbing up the grade $A\ B$ at a uniform velocity whose velocity head is measured by $A\ A' = B\ B'$. At B it commences to slow up for a stop at C. Since it is stationary at C, the

velocity head is zero and the virtual profile $A'\ B'$ runs from B' to C by a line which may or may not be straight. Assume that the train starts up and the engine exerts such force that at D it has regained the velocity it had at A or B. The ordinate $D\ D'$ must equal $A\ A'$ and the virtual profile must run from C to D'. $C\ D'$ therefore represents the virtual grade up which the train must climb. To put it in figures: Assume that $C\ D = 1300$ feet; the required velocity at D is 20 miles per hour, and therefore $D\ D' = 14.05$; the grade of $C\ D$ is 1.0 per cent and therefore $D\ D'' = 13$ feet, and $D''\ D' = 27.05$ feet; the virtual grade $C\ D'$ is therefore 2.08 per cent instead of the actual 1.0 per cent and these figures represent the actual ratio of the drawbar pulls at the engine.

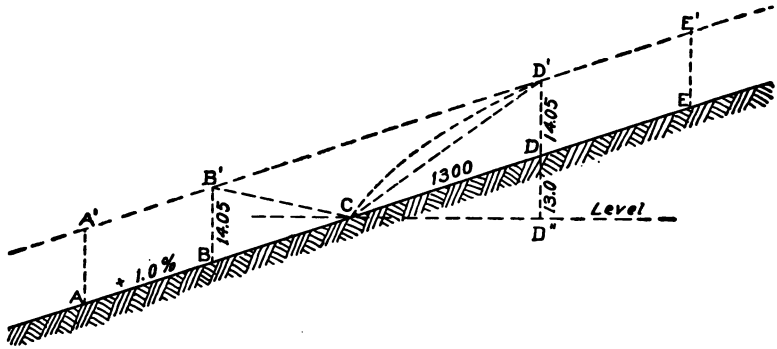

Fig. 158. Diagram Showing Action of Forces on Train Stopping on Grade

To be more precise, the virtual grade $C\ D'$ will not be a uniform grade as shown in the figure but will be a curved line which will be steeper at the beginning of the grade on account of the increased resistance to traction when starting. This is somewhat compensated by the fact that the tractive force of the engine is greater at the very low velocities. It requires, however, a little margin for safety.

The fact that the engine can increase its velocity from zero to 20 miles per hour in that distance and on that grade shows that it is capable of doing much more than run its train up the 1.0-per-cent grade at a speed of 20 miles per hour. In fact, unless the power is reduced when the train reaches D, the train will continue to gain velocity. If resistance and tractive power were independent of velocity, the train would continue to gain indefinitely, assuming

that the grade continued uniformly. But practically, when the velocity had increased to a much higher figure, the resistances would increase and the tractive power decrease until there could be no further increase in velocity.

From all the above it may be inferred that

(1) When the velocity is uniform, the virtual profile is parallel with the actual profile.

(2) When the velocity is increasing, the profiles are separating; when it is decreasing, they are approaching each other.

(3) When the velocity is zero the profiles coincide.

(4) The virtual grade at any place is a measure of the work required of the engine beyond that required to overcome merely the tractive resistances. If it is horizontal it shows that the engine is doing nothing besides overcoming the tractive resistances. If it is upward and is uniform, as in Fig. 157, it shows that it is working uniformly and is storing in the train "potential" energy which may be utilized on the return trip if it is not utilized in moving down a succeeding downgrade. If it is downward, as from B' to C, Fig. 158, it shows that the train is giving up kinetic energy, probably consuming most of it in brakes, but utilizing some of it to furnish the tractive power to run from B to C and also to overcome the grade from B to C.

181. Use, Value, and Possible Misuse of Virtual Profiles. It has been previously shown that, aside from securing the maximum traffic, the most important accomplishment for the locating engineer is to obtain low ruling grades. At the same time the cost for grading must be kept as low as possible without sacrificing the more important elements. The grade $B\,D$ in Fig. 157 is an example of the possibility of introducing a grade which is much steeper than the ruling grade, providing it is not so long that the kinetic energy of the train at the bottom of the grade is exhausted before it reaches an easier grade, and also provided that no heavy trains are ever compelled to stop on that grade. Herein lies the danger and the possible misuse of this method.

A grade might be laid out substantially as shown in Fig. 157, with the intention of running all heavy trains up that grade without stopping. Later, another railroad might require and make a grade crossing at or near C, which would occasionally require that

trains shall stop at the crossing, and such loaded trains would be unable to start against such a grade, especially since the tractive resistance to starting is so much greater than the resistance at ordinary speeds. The chief value of such a method lies in the fact that it enables the engineer to determine the actual demand on the locomotive, as it is affected by the velocity of the train. The "undulatory" profile shown in Fig. 157 will probably be much cheaper to construct than the uniform grade $A\,E$ which would involve a fill at B and a cut at D. The method of a virtual profile will show at once whether such a profile at that place will be a permissible way of economizing in spite of the fact that it introduces a 1-per-cent grade which is perhaps higher than the ruling grade. Many of the "improvements of old lines" depend on this process for their solution.

For example, a grade which always may have been harmless and unnoticed suddenly becomes important when it becomes desirable or necessary to require all heavy trains to stop at some point on it; such a case is sketched in Fig. 158. The above method indicates how such a problem may be investigated. The grade $C\,D'$ of course becomes the critical grade, but under given conditions the virtual profile will show the demand on the locomotive. Examples of this will be given later. Undulatory grades have the advantage of decreasing the cost of construction and of being harmless under given conditions, but there are some dangers.

$C\,D\,E$ in Fig. 157 is called a "hump" in the grade. In the numerical case given it is only 4.8 feet and would be harmless under almost any conditions, but if it were considerably more, and if a train when passing C had a velocity much less than 20 miles per hour, it might become stalled before reaching the summit of the hump. Slippery rails or a strong head wind may so increase the resistances against which a train works that if the computed margin of velocity head at the top of a hump is made too small it may be entirely overcome and the train may be stalled before it is safely over the hump. A velocity of 5 miles per hour, which corresponds to a velocity head of only 0.88 feet is the least margin that should be safely allowed. This is also partly due to the fact that when the velocity becomes less than 5 miles per hour the resistances per ton increase, and as the velocity drops very low they increase

very rapidly and the law on which the above calculations are based becomes inoperative.

Another danger is that a sag may be so deep that trains will acquire an excessive velocity when passing through it unless brakes are applied. This of course does not mean that the sag must not be used. It simply means that the sag will cause a waste of energy in brakes, a waste which must afterward be made up by increased work from the locomotive. This, consequently, is one of the cases which requires computation, by methods which follow, to determine whether or to what extent the sag is justifiable so that the two items of increased first cost and increased operating expenses shall be made a minimum. For example, a freight train may approach a sag with a velocity of 20 miles per hour. Its velocity head is therefore 14.05 feet. If the sag at its lowest point is 40 feet lower than the imaginary grade line on which the train could have run without changing its velocity (the grade $A\ B'$ in Fig. 157), then the velocity head of the train at the bottom of the sag would be 54.05 feet, which corresponds to a speed of 39.2 miles per hour. Although this is a permissible speed with freight trains which are equipped with air brakes and automatic couplers, it is approaching the limit, and there might be some local conditions which would render even this speed through the sag inadvisable.

182. Problems. 1. If a train is running uniformly along a level grade at a speed of 35 miles per hour and reaches a 1.2-per-cent upgrade, how far up the grade could it run before its speed is reduced to 10 miles per hour?

Velocity head for 35 miles per hour = 43.01 feet
Velocity head for 10 miles per hour = 3.51 feet

Permissible increase in elevation = 39.50 feet
Distance from bottom of grade = 39.50 ÷ .012 = 3292 feet

2. At what speed may a train approach a sag 28 feet below the normal grade line so that its maximum speed at the bottom of the sag shall not exceed 36 miles per hour?

At 36 miles per hour the velocity head = 45.51 feet
Subtracting the depth of the sag = 28.00 feet

The permissible velocity is that due to 17.51 feet or 22.3 miles per hour.

RESISTANCES

183. Train Resistance. The energy of the steam in the locomotive boiler is spent first in overcoming the various internal resistances between the boiler and the rims of the driving wheels. This engine resistance is computed later. Then the resistance due to the truck wheels of engine and tender and the atmospheric resistance together make up the difference (on a level track and at uniform velocity) between the adhesion at the drivers and the draw-bar pull. The draw-bar pull is spent, as discussed herewith, in overcoming the effect of (1) grade, (2) curvature, (3) the normal track resistance on a straight-level track at uniform velocity, (4) the force required to accelerate and (5) the starting resistance.

(1) *Grade Resistance.* Grade resistance is readily determinable with mathematical accuracy and equals 20 pounds per ton (of 2000 pounds) for each per cent of grade. For example, the grade resistance on a 1.2-per-cent grade is $20 \times 1.2 = 24$ pounds per ton.

(2) *Curvature Resistance.* Curvature resistance is usually considered to be the equivalent of a .035-per-cent grade for each degree of curvature, although the resistance varies somewhat, depending on the velocity, and on the superelevation of the outer rail, the resistance being greater if the velocity is much less than that for which the superelevation was designed. This is the value usually taken in computing the compensation for curvatures (see article 176). Then the resistance in pounds per ton equals $20 \times .035 = 0.7$ pound for each degree of curvature.

Examples. 1. What is the curvature resistance per ton on a 4-degree curve?
Solution. $4 \times 0.7 = 2.8$ pounds per ton

2. What is the combined curvature and grade resistance on a 6-degree curve, located on a 2.2-per-cent grade?

Solution. The grade equivalent to the curve $= 6 \times .035 = 0.21$, which added to $2.2 = 2.41$ per cent, the equivalent grade. $20 \times 2.41 = 48.2$ pounds per ton, the resistance.

(3) *Normal Track Resistance.* Normal track resistance is a combination of several resistances which are variously affected by changes in conditions. The resistance to the rolling of wheels on the rails is a very small part of the total resistance. Accurate tests of journal friction show that the friction of axles in their bearings is actually less at higher velocities, probably because the resulting higher

temperature reduces the friction. The total varies with the number of cars in the train. The resistance per ton is much lower as the load per wheel increases. The atmospheric resistance of freight trains evidently depends on whether the train is made up of only one type of car (box, flat, or gondola), or of a combination of types, which would increase that resistance. Numerous experiments have been made, by placing a dynamometer between the locomotive and first car, to determine the amount of the tractive force and to discover its variation with velocity and its other laws. Of course it was necessary, when analyzing the results of these tests, to deduct first the effect of grade, curvature, and acceleration or retardation; but even then the results are so far from uniform that no set of numerical values can be uniformly applied to all grades of track. This variation is due to the very evident fact that the resistance would be less on a high-grade, well-kept track, with heavy rails than on a cheap, rough track, with light rails. But there is one very significant and surprising result which may be deduced from each series of tests, and that is, that a formula which makes the resistance equal a constant times the number of tons plus another constant times the number of cars, but with no variation depending on velocity, will satisfy the dynamometer results as closely as any other equally simple law. This statement applies to freight trains between the velocities of 5 miles and 35 miles per hour. When starting the resistance is greater. At higher velocities than 35 m.p.h. the resistance is also greater, but since the economies of reduced resistance apply chiefly to freight trains at usual working velocities, the simplicity of the above law is important. Each set of tests on any given piece of track will give a new pair of constants for the resistance formula. A compilation of the results of many tests gave the following, issued by the American Railway Engineers Association, as an average formula:

$$R=2.2\ T+121.6\ C \qquad (105)$$

in which R is total resistance at uniform velocity on a level tangent; T is total weight of cars and contents, in tons; and C is number of freight cars in train.

It should be clearly understood that the formula does not necessarily give the actual resistance for any given case, since the

resistance will depend on the actual condition of the track, but the result will be a good average result and *for comparative purposes* the formula is useful.

The resistance of trains at higher velocities than 35 miles per hour must be considered as depending on velocity. The formula used by the Baldwin Locomotive Works is

$$R = 4.3 + 0.0017\ V^2 \qquad (106)$$

in which R is the resistance per ton, and V is the velocity in miles per hour. The formula is particularly applicable to passenger trains having cars weighing 45 tons and over. For lighter cars, the freight-train formula should be used. The formula should not be used for low velocities, especially those below 10 miles per hour, nor for light-weight cars.

Example. Assume that there are 33 freight cars weighing, with contents, 2200 tons. What is the total resistance behind the engine?
Applying equation (105)

$$R = 2.2 \times 2200 + 121.6 \times 33 = 8853 \text{ pounds}$$

As an illustration of variations in results, depending on variations in track condition, some tests on the Baltimore & Ohio Railroad were reduced to a formula similar to equation (105) but with the constants, 2.78 and 113.9. Using these constants and applying the formula to the above numerical case, the computed value of R would be 9875, an increase of nearly 12 per cent. This variation shows the uselessness of attempting to apply any definite numerical values and to expect accuracy unless the resistance of the particular track in question has been determined by actual test.

(4) *Accelerative Force.* Accelerative force has been computed theoretically in article 179. The formula for acceleration may also be applied to determine how far the kinetic energy in a train will help to force it up a grade which is greater than that up which the locomotive could haul such a train indefinitely.

(5) *Starting Resistance.* As previously stated, the resistance per ton when starting a train is considerably in excess of the ordinary resistance. When cars have been left standing for several hours, or even days, especially in winter weather, it may take a force of 40 pounds per ton to produce motion. The bearings become "frozen". But such resistance is only momentary and may be

partly overcome by the impact of moving cars or engine striking against the stalled cars. When an engineer reverses his engine, backs it against the cars, and then immediately reverses again so as to go forward, he accomplishes three things: (1) the journals become loosened from the comparatively rigid condition they will assume even during a short stop; (2) the springs of the couplers will become compressed during the small backward motion and their expansion during forward motion will materially assist the forward motion; (3) if the train is very long, the total slack in the couplers is very considerable and the locomotive will have moved several feet before the last car begins to move and the cars are started one by one. Such devices in operation reduce to a variable extent the resistance which would be encountered if all cars were started at the same instant. A series of tests on the Rock Island system gave results with an ordinary range from 10 to 18 pounds per ton and averaging 14.1 pounds. An extreme value of 30 pounds was noted for "frozen bearings" and a low extreme of only 6 pounds extra when the stop was only momentary. Since a juggling of the train can produce virtually the same result as a mere momentary stop, the necessary extra starting resistance for a limiting case will be considered as only 6 pounds per ton in solving some numerical problems in a later article.

Example. How much draw-bar pull will be required to haul a freight train of 10 cars, each weighing 70 tons, and a caboose weighing 15 tons, at a uniform velocity of 15 miles per hour up a 0.9-per-cent grade?

Solution. The only significance of the 15 m.p.h. in the solution is the fact that it is between 5 and 35 and that equation (**105**) is applicable. The grade resistance per ton is $20\times0.9=18$ pounds, and for the 11 cars weighing 715 tons it is $715\times18=12{,}870$ pounds. The tractive resistance, by equation (**105**), is

$$R=2.2\times715+121.6\times11=2911 \text{ pounds}$$

Adding the grade resistance, the total resistance would be 15,781 pounds.

The above problem assumed gondola cars weighing 40,000 pounds and each carrying 100,000 pounds and a 15-ton caboose. Suppose that the train consisted of empties, say 35 empties at 20 tons each, or 700 tons, and the 15-ton caboose. The total weight being the same, the grade resistance is the same. But the number of cars being greater, the tractive resistance is greater and

$$R=2.2\times715+121.6\times36=5951 \text{ pounds}$$

which is an increase of 3040 pounds, and the tractive resistance is more than doubled. It should be noted that if there were no grade, the tractive resistance would be only 2911 pounds for the loaded train and 5951 pounds (over twice as much) for the empty train of the same gross weight. On the other hand, on the 0.9-per-cent grade the resistance of the loaded train would be 15,781 pounds and that of the train of empties $5951+12{,}870=18{,}821$ pounds, which is only 19 per cent greater. The average tractive resistance per ton of the loaded train is $2911\div 715=4.07$ pounds, while that of the empty train is $5951\div 715=8.32$ pounds. The grade resistance is constant in either case at 18 pounds per ton. The character of the train load, whether loaded or consisting of a long train of empties of the same gross weight, is thus a matter of great importance on a level or nearly level road and becomes of much less importance on a grade of even 0.9 per cent. On a 2-per-cent grade the tractive resistance is comparatively small and variation in the character of the loading is of still less importance.

Example. How much tractive force will be required, using the data of the previous example, to increase the velocity from 15 m.p.h. to 20 m.p.h. in a distance of 500 feet?

Solution. Applying equation (104) we have $V_1=15$, $V_2=20$, and $s=500$. Then

$$P=\frac{70}{500}(20^2-15^2)=24.5 \text{ pounds per ton}$$

For the 715-ton train, this will require an extra pull of 17,518 pounds. This is the equivalent of a $24.5\div 20=1.225$-per-cent grade. Whether the locomotive has sufficient tractive force to pull 15,781 pounds of tractive force and grade resistance and 17,518 pounds more for acceleration, or a total of 33,299 pounds, is a matter to be studied under "power of the locomotive", article 189. The further question would arise, could the locomotive make steam fast enough to produce this energy? This will be considered in article 189.

Example. What is the tractive resistance behind a passenger engine of a load of 4 cars, each weighing 52 tons and traveling at a velocity of 60 miles per hour?

Solution. Substituting in equation (106) the value of $V=60$, we obtain $R=10.42$ pounds per ton, and for the 208 tons the draw-bar pull would be 2167 pounds.

Irrespective of the resistance of the locomotive itself, considered later, this pull of 2167 pounds at a velocity of 60 m. p. h., or 88 feet per second, is the equivalent of $88 \times 2167 = 190{,}696$ foot-pounds per second, or, dividing by 550, equal to 346 horsepower.

PULLEY POWER OF LOCOMOTIVES

184. Rating of Locomotives. Since it is very important for the economical operation of roads that each locomotive should be loaded to the limit of what it can efficiently haul, and since, as shown in article 183, the hauling power of a locomotive, especially on a flat grade, depends on the number of cars as well as on their gross weight, it is important to determine for each locomotive a loading which will measure its power and which is independent of the number of cars or of the rate of grade. This loading is called its "rating" and by applying to the rating a proper correction, depending on the number of cars and grade, the hauling power or the proper loading of that locomotive for any grade may be readily determined.

Let P be pulling power of the locomotive, or the tractive power as measured at the rim of the drivers; E weight of engine and tender, in pounds; W weight of cars behind tender, in pounds; R rate of grade, or ratio of vertical to horizontal; K a constant which, as determined by tests, is the factor 2.2 pounds per ton, in equation (**105**); C a constant which, as determined by tests, is the factor 121.6 pounds per ton, in equation (**105**); N number of cars in the train; and A the desired rating. Then

$$P = (E+W)\ (R+K) + NC$$

transforming,

$$\frac{P}{R+K} - E = W + N\frac{C}{R+K}$$

The right-hand side of this equation is the weight of the train behind the tender plus the number of cars times a quantity made up of two constants and the rate of grade. This right-hand side of the equation is called the rating, or A. Values of the fraction $C \div (R+K)$, in tons per car, which are independent of engine or train characteristics, are tabulated for various rates of grade, as given in Table XVIII. In computing these values, since C and K are resistances per ton, R must be the resistance per ton for the rate of grade considered.

TABLE XVIII

Values of $C \div (R+K)$ for Various Grades

(In tons per car)

Grade R (per cent)	Tons per Car $C \div (R+K)$	Grade R (per cent)	Tons per Car $C \div (R+K)$	Grade R (per cent)	Tons per Car $C \div (R+K)$	Grade R (per cent)	Tons per Car $C \div (R+K)$	Grade R (per cent)	Tons per Car $C \div (R+K)$
Level	55	0.5	10.0	1.0	5.5	1.5	3.8	2.0	2.88
0.1	29	0.6	8.5	1.1	5.0	1.6	3.6	2.1	2.75
0.2	20	0.7	7.5	1.2	4.6	1.7	3.4	2.2	2.63
0.3	14	0.8	6.7	1.3	4.3	1.8	3.2	2.3	2.52
0.4	12	0.9	6.0	1.4	4.0	1.9	3.0	2.4	2.42

Examples. 1. Assume that the pulling power P of a locomotive, or the power at the rim of the drivers, computed as in article 190, was estimated to be 33,742 pounds and that the weight E of the engine and tender was 315,000 pounds. On a 0.5-per-cent grade $R = .005$ and $K = 2.2$ pounds per ton or .0011 pound per pound.

Solution.

$$A = \frac{P}{R+K} - E = \frac{33{,}742}{.005+.0011} - 315{,}000 = 5{,}216{,}000 \text{ pounds} = 2608 \text{ tons}$$

which is the rating for a 0.5-per-cent grade. Similar ratings for that locomotive may be easily computed for all rates of grade. Such a locomotive may haul on any grade a load W such that $A = W + N\, C \div (R+K)$. From Table XVIII we find that, for a 0.5-per-cent grade, $C \div (R+K) = 10$. If there are 40 cars in the train, then

$$2608 = W + (40 \times 10)$$
$$W = 2608 - 400 = 2208 \text{ tons}$$

which is an average of 55 tons per car. If the cars are of uniform weight (such as empties, weighing say 18 tons) then $W = 18\, N$, and the equation becomes

$$2608 = 18\, N + 10\, N = 28\, N$$

and

$$N = 93$$

which means that such an engine can haul a load of 93 empties, each averaging 18 tons, up a 0.5-per-cent grade at a uniform velocity. Note that this ignores curvature resistance, which if it exists is assumed to be provided by a compensation of the grade.

2. What would be the rating for the same locomotive on a long 1.6-per-cent grade?

Solution.

$$A = \frac{33{,}742}{.016+.0011} - 315{,}000 = 1{,}658{,}000 \text{ pounds} = 829 \text{ tons}$$

By Table XVIII, the "adjustment" in tons per car is 3.6. Again considering empties weighing 18 tons, we would have

$$829 = 18\, N + 3.6\, N = 21.6\, N$$

and

$$N = 38$$

If all cars were loaded and had an average weight of 56 tons, we would have

$$829 = 56\,N + 3.6\,N = 59.6\,N$$

N = nearly 14, or say 13 loaded cars and the caboose

In the above examples the pulling power P is determined on the basis of the locomotive working at the maximum velocity M at which it can maintain full stroke. See article 190. This represents practically the maximum power of the locomotive. The velocity M is usually from 4 to 7 miles per hour and is as low as should be allowed on maximum grades, since an attempt to utilize a slightly higher tractive force at a somewhat lower velocity would probably result in stalling the train if an unexpected resistance in the track slightly increased the normal resistance.

185. Units of Operation. A large part of the calculations in railroad economics consists of a valuation of changes in alinement or the financial value of a reduction of distance, curvature, rise and fall, and ruling grade. Formerly such calculations were made exclusively on the basis of the cost of an average *train-mile*, especially as this is shown to be surprisingly constant for roads of all characters, long and short, heavy traffic and light traffic. The general method was to take up each item in turn of the average cost of operating trains and to estimate the effect of a change in alinement on the normal average percentage of each item. Some of the items are affected very materially; others are affected very little or not at all. The normal average for each item was then multiplied by the percentage by which that item was estimated to be affected by that unit change in alinement conditions, and then the sum of these products would be the computed percentage by which that unit change of alinement would affect the average cost of a train-mile. Further study has shown that the cost of fuel, for example, for freight trains is disproportionately high. Therefore, when comparing the relative costs of operating freight locomotives on two different grades, it will not do to base the estimate of increased fuel demand on the average cost of fuel for locomotives of all kinds. But it has become increasingly apparent that the effect of grade, for example, on the cost of operating a train is largely dependent on the weight of the train, on the character of the locomotive and its rating. Therefore the effect of grade cannot be measured by any one factor times the number of train miles involved.

Some of the elements of variation of operating expenses are more accurately measured by the number of *ton-miles*. A study of the effect of rolling stock on track maintenance shows that it is largely dependent on train velocity and also on intensity of axle loading. Although exact ratios are not computable, it has been broadly estimated that passenger trains, having a much higher average velocity, are responsible for twice as much track damage as the same tonnage of freight trains; also that locomotives, having heavier axle loads and not being truly counterbalanced, are responsible for twice as much track damage as the cars of the same train, which would mean that the locomotive of a high-speed passenger train would do four times as much damage as the car axles of a slow freight.

The *passenger-mile*, although frequently used in statistics of service rendered by railroads, has little or no relation to the cost of service and therefore is not used in problems of changes in alinement and grade.

The *car-mile* is a useful unit for some special purposes. If a steel passenger car weighs 100,000 pounds and carries even its maximum load of 80 passengers with an average weight of 125 pounds, the total live load (10,000 pounds) is only 10 per cent of the dead load. And when, as is usual, the actual live load is only a part, and perhaps a small part, of the possible load, then it makes but little difference in the tractive force required for hauling, especially on low grades, whether the car is loaded or empty. Other items of expense vary almost directly as the number of car-miles.

The *engine-mile* is similarly a useful unit in estimates in which certain costs vary as the number of engine-miles and nearly or quite regardless of variations in other factors.

Another element of practical cost in the operation of trains over a division is the *total time* required for a run by the slow freight trains. The old methods would invariably indicate that the most economical grades, using locomotives of a certain power, were those which would permit the maximum train load, even at the slowest velocity. But it was later developed that it is actually more economical to run somewhat lighter trains at a higher velocity; and that there is a certain combination of train load and velocity beyond which, if the train load is increased and the time of run increased,

the extra fuel burned, the extra time of the train crews, and the extra blocking of the tracks (especially on a single-track road) more than offset the economy of increased tonnage in one train. A consideration of these various elements and units of operation shows the impracticability of adopting any uniform unit values for one foot (or mile) of distance saved, or of one degree of curvature saved, or for each $\frac{1}{10}$ per cent of grade lowered, which would be sufficiently accurate for universal applicability, and that the only accurate method of studying the value of a proposed change of alinement for handling an assumed amount of business, with an assumed type of locomotive, is to estimate the power of that locomotive on each of the two grades (or other variations of alinement) and the relative number of trains, with their cost of operation, in order to handle that business. If the problem is a suggested change in an existing road, the investigator has the advantage of an opportunity to study what the locomotive in use can do on the existing alinement and grades, and he has only to compute the effect of the changes. If the problem is a suggested change in a proposed new line, the cost of operation under both conditions must be estimated.

186. Types of Locomotives. The variations in locomotive service have developed all conceivable types as to total weight, ratio of total weight to weight on drivers, types of running gear, relation of steaming capacity to tractive power, etc. The method of classification on the basis of the running gear is very simple. The number of wheels on both rails of the pilot truck, if any, is placed as the first of three numbers. If there is no pilot truck, the character 0 is used. This is followed by the number of drivers and then by the number of trailing wheels, if any. For example, a Pacific-type engine has four wheels on the pilot truck, six driving wheels, and two trailing wheels under the rear of the boiler. The wheel base is symbolized as 4-6-2. The most common types of locomotives, with their popular names and wheel-base symbols, are

American	4–4–0	Consolidation	2–8–0
Columbia	2–4–2	Mikado	2–8–2
Atlantic	4–4–2	Mastodon	4–8–0
Mogul	2–6–0	Santa Fe	2–10–2
Ten-wheel	4–6–0	Mallet	A–B–B–A
Pacific	4–6–2	A = truck wheels, usually	2 or 0
Six-wheel switcher	0–6–0	B = drivers, varying from	4 to 10

The Interstate Commerce Commission report for 1912 showed 534 locomotives of the "Mallet" type, out of a total of 62,262 in the U. S. This is less than 1 per cent but, considering that the growth in numbers of this type in one year was nearly 23 per cent while the increase in all classes was about 1½ per cent, or that more than 10 per cent of the net increase was of this type, it deserves special mention. Excluding freak variations, they are always "four-cylinder compounds", one pair of cylinders discharging into the other pair and then exhausting. They have from five to ten driving axles, and have a length of engine wheel-base up to nearly 60 feet. Sometimes the boiler is made "flexible" by a set of accordion-shaped steel rings forming a joint in the boiler shell. The boiler proper is on one side of the joint and the feed-water heater, the reheater, and perhaps the superheater are on the other side. Or, the boiler shell is made rigid, one end is rigidly attached to the frame carrying the high-pressure cylinders and the other end is supported on a bearing on the truck frame which carries the low-pressure cylinders and the drivers operated by them. The low-pressure truck frame swings around a pivot in the fixed frame and this so cuts down the length of rigid wheel-base that these engines are operated successfully on 20-degree curves, and are therefore practicable on any road having reasonable alinement. These locomotives are chiefly used by roads handling large quantities of heavy freight, such as coal, up long stretches of heavy grades, where the demand for tractive power is very great. The tractive power of some of these locomotives is over 110,000 pounds, which is nearly four times as great as that of the average locomotive in the United States.

187. Oil-Burning Locomotives. In 1912 over one-sixth of all the locomotives west of the Mississippi River used oil as fuel. Some of the advantages in using oil are as follows: (1) the British thermal units in one pound of oil vary from about 19,000 to 21,000; those in a pound of coal vary from perhaps 14,000 down to 5000 for the poorer grades of lignite found in the western part of the United States and this means a great reduction in the cost of carrying and storing fuel, measured in heat units; (2) the cost of handling fuel is reduced and that of disposing of ashes is eliminated; (3) engine repairs are reduced in many respects although it is said that the increased cost of fire-box repairs, due to the intense heat of the oil

flame, offsets any reduction in other items; (4) the fires can be more easily controlled and waste of heat reduced during stoppages or when drifting down grade; (5) wayside fires due to sparks are altogether eliminated; (6) there is a practical limitation (see article 189) to the amount of coal that one fireman can feed to a fire, but there is no such limitation when using oil; (7) there is an equality in cost of heat units when a 42-gallon barrel of oil, weighing 7.3 pounds per gallon, costs 60 cents and a ton (2000 pounds) of coal, having two-thirds as many heat units per pound, costs $2.61, or 4.35 times as much. The other items of difference almost invariably favor the oil and might make it more desirable even when the ratio of cost seemed to favor the coal. Oil is used very extensively west of the Mississippi River, where in many places oil is plentiful and cheap and coal is poor in quality and high in price.

188. Relation of Type to Service and to Track Conditions. Economy in operating conditions requires a thorough co-ordination between the characteristics of the locomotive, the fuel it is to burn, the roadbed and track it is to run on, and the character of service it is to render. It may not even be the best economy to use the same type of locomotive, for a given kind of service, on consecutive divisions of the same road.

Wheel-Load to Rail-Weight. Since the support which the rail receives from the ties and ballast is uncertain and variable, any rule for the relation must be empirical and approximate. The rule adopted by the Baldwin Locomotive Works ("300 pounds of wheel per pound of rail per yard") may be used in making a diagram from which the relation between total weight on driving wheels, number of drivers, and weight of rail, may be readily observed, Fig. 159.

For example, if it is desired to use a type of locomotive with 170,000 pounds on the drivers and also 75-pound rails, four pairs of drivers will be needed. By using 95-pound rails the same weight on drivers could be placed on three axles. As another example, a Pacific-type locomotive, with 150,000 pounds on its six drivers, should have a rail with a minimum weight of 83 pounds, or say an 85-pound rail.

189. Power of Locomotives. The tractive power of a locomotive, or its "draw-bar pull" is limited by the adhesion of the drivers, and by the capacity of the boiler to make steam. The

adhesion of the drivers is a fairly definite ratio of the weight on the drivers. Under very favorable conditions, with a dry rail and using sand, a ratio of one-third and over can be obtained. As

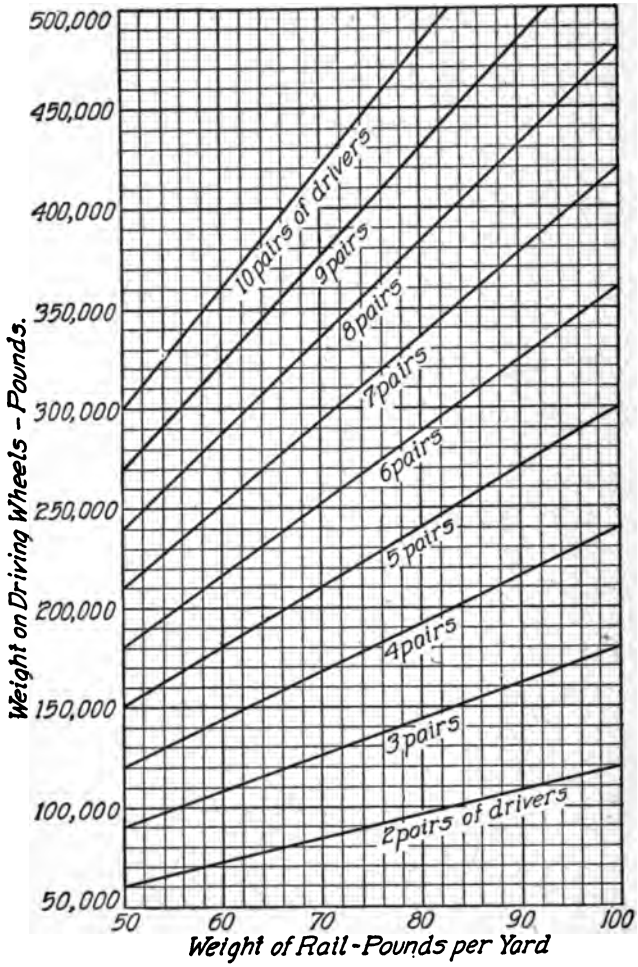

Fig. 159. Curves for Finding the Number of Drivers Needed for Given Weight on Driving Wheels and Weight of Rails

an ordinary value one-fourth ($\frac{10}{40}$), or perhaps nine-fortieths is more usual. Under unfavorable conditions, the ratio reduces to one-fifth ($\frac{8}{40}$), or less. The capacity of the boiler to make steam depends on the grate area, the heating surface, and (in the case of

modern heavy freight locomotives) the capacity of the fireman to shovel coal.

Experience shows that an average fireman, when he must maintain the full power of the locomotive for long periods of time, can handle about 4000 pounds of coal per hour, although individual performances, in special test cases and for short periods of time, have given much higher values. It may occasionally be admissible to estimate on extra work up to 5000 pounds per hour for a short period, provided it is preceded or followed by easier work. The use of automatic stokers can raise this hourly consumption very considerably (say up to 7000 pounds) or up to the capacity of the locomotive to burn coal properly, whatever it may be for the particular type. There is of course no such limitation in the use of oil-burning locomotives, which now include about 7 per cent of the total number in the United States. These are the exceptional cases.

The power developed by any given type of locomotive depends largely on the characteristics of the coal used. A British thermal unit (symbolized as B.t.u.) is the quantity of heat required to raise the temperature of 1 pound of pure water 1° Fahrenheit, when the water is at or near its maximum density at 39.1° Fahrenheit. When it is said that a certain grade of coal has 14,000 B.t.u. it means that the heat in 1 pound of that coal will raise the temperature of 14,000 pounds of water 1°, or, approximately, 100 pounds of water 140°. But although it only requires 180.9 heat units to heat water from 32° to 212°, it requires 965.7 more heat units to change it from water at 212° to steam at 212°. It requires only 53.6 more heat units to change it from steam at 212° to steam at 387.6° or with a pressure of 200 pounds per square inch.

A study of locomotive tests made at the St. Louis Exposition resulted in the compilation of Table XIX, which is copied from the Proceedings of the American Railway Engineering Association, and is now included as Table 1, in the Economics section of their Manual. It was found that the steam produced per square foot of heating surface is very nearly proportional to the coal burned per square foot of heating surface. The results are purposely made about 5 per cent below the results obtained in the St. Louis tests to allow for ordinary working conditions.

TABLE XIX

Average Evaporation in Locomotive Boilers Burning Bituminous and Similar Coals of Various Qualities, and for Various Quantities Consumed per Square Foot of Heating Surface per Hour

(Based on feed water at 60° Fahrenheit, and boiler pressure 200 pounds)

Coal per Square Foot of Heating Surface per Hour (lb.)	Steam per Pound of Coal of Given Thermal Value (lb.)					
	15,000 B.t.u.	14,000 B.t.u.	13,000 B.t.u.	12,000 B.t.u.	11,000 B.t.u.	10,000 B.t.u.
0.8	7.86	7.34	6.81	6.29	5.76	5.24
0.9	7.58	7.07	6.57	6.06	5.56	5.05
1.0	7.31	6.82	6.34	5.85	5.36	4.87
1.1	7.06	6.59	6.12	5.65	5.18	4.71
1.2	6.82	6.37	5.91	5.46	5.00	4.55
1.3	6.59	6.15	5.71	5.27	4.83	4.39
1.4	6.37	5.95	5.52	5.10	4.67	4.25
1.5	6.17	5.76	5.35	4.94	4.52	4.11
1.6	5.97	5.57	5.18	4.78	4.38	3.98
1.7	5.79	5.40	5.02	4.63	4.25	3.86
1.8	5.61	5.24	4.86	4.49	4.12	3.74
1.9	5.44	5.08	4.71	4.35	3.99	3.63
2.0	5.27	4.92	4.57	4.22	3.86	3.51
2.1	5.12	4.78	4.44	4.10	3.75	3.41
2.2	4.97	4.64	4.31	3.98	3.64	3.31
2.3	4.83	4.51	4.19	3.86	3.54	3.22
2.4	4.69	4.38	4.07	3.75	3.44	3.13
2.5	4.56	4.26	3.95	3.65	3.34	3.04
2.6	4.44	4.14	3.84	3.55	3.25	2.96
2.7	4.32	4.03	3.74	3.46	3.17	2.88
2.8	4.21	3.93	3.64	3.37	3.09	2.80
2.9	4.10	3.83	3.55	3.28	3.01	2.73
3.0	3.99	3.73	3.46	3.19	2.93	2.66

The quantity of steam evaporated for intermediate quantities or qualities of coal can be found by interpolation.

On bad-water districts deduct the following from tabular quantities:

For each $\frac{1}{16}$ inch of accumulated scale..... 10 per cent

For each grain per U. S. gallon of foaming salts in the average feed water..... 1 per cent

190. Power Calculations. *Illustrative Example.* Assume that a Mikado locomotive, having a total heating surface of 2565 square feet is fired with coal whose samples test 13,000 B.t.u. On the basis that a fireman can handle 4000 pounds of coal per hour and maintain such work throughout his run, the coal may be fed at the rate

of $\frac{4000}{2565} = 1.56$ pounds per hour per square foot of heating surface. If the air-dried mine samples of the coal tested 13,000 B.t.u., the average run-of-car coal would have about 90 per cent of this, or 11,700 B.t.u. Interpolating in Table XIX for 1.56 and 11,700 we find that the pounds of steam per pound of coal would be 4.72. But since the locomotive is designed for use at 175 pounds gage pressure, instead of 200, as in Table XIX, the amount of steam produced will be about 0.3 per cent more, or say 4.73. The uncertainties of firing are so great that such small corrections may be ignored. But considering that a superheater is used in this locomotive, and that, with the usual superheater proportions and efficiency, 0.85 pound of superheated steam may be considered as having the same volume and pressure as 1 pound of saturated steam, the amount of steam developed by 1 pound of coal is equivalent to $4.73 \div 0.85 = 5.56$ pounds. Then the equivalent amount of steam developed per hour equals $5.56 \times 4000 = 22{,}240$ pounds.

The weight of steam used per stroke may be computed most easily by utilizing Table XX, which is also taken (but somewhat amplified) from the Proceedings of the American Railway Engineering Association, and now included as Table 2 in the Economics section of their Manual. The weight of steam per foot of stroke for 22 inches diameter and 175 pounds gage pressure is 1.106 pounds and for a stroke of 28 inches ($2\frac{1}{3}$ feet) it is 2.581 pounds. For a complete revolution of the drivers it is $4 \times 2.581 = 10.324$ pounds. Since the engine can develop the equivalent of 22,240 pounds of steam per hour and will use 10.324 pounds at one revolution, it can run at a speed of $22{,}240 \div 10.324 = 2154$ revolutions per hour, or 35.9 revolutions per minute, at full stroke and maintain full boiler pressure. The drivers are 57 inches in diameter and therefore have a circumference of $(57 \div 12) \times 3.1416 = 14.923$ feet. The maximum engine speed for full stroke is $35.9 \times 14.923 = 535.7$ feet per minute. Multiplying by 60 and dividing by 5280, or dividing by 88, we have 6.087 miles per hour as the maximum speed at which full stroke can be maintained.

In Table XXI, also taken from the proceedings of the American Railway Engineering Association and now included as Table 4 in the Economics section of the Manual, are given the pounds of steam

TABLE XX

Weight of Steam Used in One Foot of Stroke in Locomotive Cylinders

(Cylinder diameter is for high-pressure cylinders in compound locomotives)

Diameter of Cylinder (inches)	Weight of Steam per Foot of Stroke for Various Gage Pressures						
	220 Pounds per Square Inch (lb.)	210 Pounds per Square Inch (lb.)	200 Pounds per Square Inch (lb.)	190 Pounds per Square Inch (lb.)	180 Pounds per Square Inch (lb.)	170 Pounds per Square Inch (lb.)	160 Pounds per Square Inch (lb.)
12	0.405	0.389	0.370	0.354	0.337	0.321	0.304
13	0.475	0.456	0.435	0.415	0.396	0.376	0.357
14	0.551	0.529	0.504	0.482	0.459	0.436	0.414
15	0.633	0.607	0.579	0.553	0.527	0.501	0.476
15½	0.675	0.649	0.618	0.590	0.562	0.535	0.508
16	0.720	0.691	0.658	0.629	0.599	0.570	0.541
17	0.812	0.780	0.744	0.710	0.676	0.643	0.611
18	0.911	0.875	0.834	0.796	0.759	0.722	0.685
18½	0.962	0.924	0.881	0.841	0.801	0.762	0.724
19	1.015	0.975	0.928	0.887	0.845	0.804	0.763
19½	1.069	1.027	0.978	0.934	0.890	0.847	0.804
20	1.125	1.080	1.029	0.983	0.936	0.891	0.846
20½	1.181	1.134	1.081	1.032	0.984	0.936	0.888
21	1.240	1.191	1.134	1.083	1.032	0.982	0.932
22	1.361	1.307	1.245	1.189	1.133	1.078	1.023
23	1.487	1.428	1.361	1.300	1.238	1.178	1.118
24	1.620	1.555	1.482	1.416	1.348	1.283	1.218
25	1.758	1.688	1.608	1.536	1.462	1.392	1.322
26	1.901	1.825	1.739	1.661	1.582	1.506	1.430
27	2.050	1.968	1.875	1.792	1.706	1.624	1.542
28	2.204	2.117	2.017	1.926	1.835	1.745	1.657

For weight of steam used per revolution of drivers at full cut-off:

Multiply the tabular quantity by four times the length of stroke in feet for simple and four-cylinder compounds. For two-cylinder compounds multiply by two times the length of stroke.

per indicated-horsepower hour for simple and for compound locomotives for various velocities, which are multiples of M, the maximum velocity at which the boiler can maintain steam at full pressure. The table is computed on the basis of 200 pounds gage pressure, but factors are given for other pressures. For example, continuing the above numerical problem, the pounds of steam per i.h.p.-hour, for a simple locomotive, at M velocity, and at 200 pounds pressure, taken from Table XXI, is 38.30; for 175 pounds pressure we must multiply by the factor 101.7, which makes

TABLE XXI

Maximum Cut-Off and Pounds of Steam per I.H.P.-Hour for Various Multiples of *M*

(*M* is maximum velocity in miles per hour at full cut-off, with boiler pressure at 200 pounds per square inch)

Velocity	Cut-Off (per cent)	Pounds Steam per I.H.P.-Hour		Velocity	Cut-Off (per cent)	Pounds Steam per I.H.P.-Hour	
		Simple	Compound			Simple	Compound
1.0 *M*	Full	38.30	25.80	2.9 *M*	38.5	24.37	21.04
1.1 "	94.4	36.46	24.36	3.0 "	37.0	24.22	21.21
1.2 "	89.1	34.89	23.24	3.2 "	34.2	24.00	21.57
1.3 "	84.3	33.56	22.35	3.4 "	31.8	23.85	21.93
1.4 "	79.7	32.41	21.65	3.6 "	29.8	23.8	22.27
1.5 "	75.4	31.40	21.14	3.8 "	28.0	23.8	22.57
1.6 "	71.4	30.49	20.77	4.0 "	26.4	23.87	22.85
1.7 "	67.7	29.67	20.52	4.25 "	24.7	24.05	23.22
1.8 "	64.3	28.93	20.40	4.50 "	23.3	24.24	23.56
1.9 "	61.0	28.25	20.40	4.75 "	22.1	24.44	23.85
2.0 "	58.0	27.62	20.40	5.00 "	21.1	24.64	24.15
2.1 "	55.2	27.05	20.40	5.5 "	19.5	24.98	24.70
2.2 "	52.6	26.52	20.40	6.0 "	18.4	25.20	
2.3 "	50.1	26.06	20.40	6.5 "	17.6	25.45	
2.4 "	47.8	25.67	20.40	7.0 "	17.1	25.60	
2.5 "	45.7	25.32	20.47	7.5 "	16.7	25.70	
2.6 "	43.7	25.02	20.60	8.0 "	16.4	25.80	
2.7 "	41.8	24.76	20.73	9.0 "	16.1	25.90	
2.8 "	40.1	24.54	20.88				

For steam per i.h.p.-hour for other boiler pressures take the following percentages of values given in table:

160 lb., 103 per cent	180 lb., 101.3 per cent	210 lb., 99.5 per cent
170 lb., 102.1 per cent	190 lb., 100.6 per cent	200 lb., 99.2 per cent

the quantity 38.95. Dividing this into 22,240, the steam produced per hour, we have 571.0, the i.h.p. at *M* velocity. Multiplying this by 33,000, the foot-pounds per minute in one horsepower, and dividing by 535.7 the velocity in feet per minute, we have 35,174, the cylinder tractive power in pounds, when burning 4000 pounds of coal per hour and running at 6.087 m.p.h.

To obtain the draw-bar pull, we must deduct the engine resistances which may be computed as given in Table XXII, also taken from the Proceedings of the American Railway Engineering Association and now included as Table 7 in the Economics section of the Manual.

TABLE XXII
Locomotive Resistances

Total Locomotive Resistance is $A+B+C$, in which

A = resistance between cylinders and rims of drivers, and in pounds
$= 18.7\ T + 80\ N$ in which T = tons weight on drivers and
N = number of driving axles.

B = resistance of engine and tender trucks, and in pounds
$= 2.6\ T + 20\ N$ in which T = tons weight on engine and tender trucks
and N = number of truck axles.

C = head-end or "air" resistance, and in pounds
$= .002\ V^2 A$ in which V = velocity in miles per hour, and
A = end area of locomotive.

On the basis that the end area averages 125 square feet, the last formula becomes $C = 0.25\ V^2$. The number of pounds air resistance for various velocities is as given below.

Velocity V	Resistance C	Velocity V	Resistance C	Velocity V	Resistance C	Velocity V	Resistance C	Velocity V	Resistance C	Velocity V	Resistance C
1	0.25	8	16.00	15	56	22	121	29	210	36	324
2	1.00	9	20.25	16	64	23	132	30	225	37	342
3	2.25	10	25.00	17	72	24	144	31	240	38	361
4	4.00	11	30	18	81	25	156	32	256	39	380
5	6.25	12	36	19	90	26	169	33	272	40	400
6	9.00	13	42	20	100	27	182	34	289	50	625
7	12.25	14	49	21	110	28	196	35	306	60	900

Draw-bar pull on level tangent equals the cylinder tractive power less the sum of the engine resistances.

At low speeds, the adhesion of the drivers should be considered and available draw-bar pull should never be estimated greater than 30 per cent of weight on drivers at starting with use of sand, or 25 per cent of weight on drivers at running speeds.

Applying Table XXII to the numerical problem, item A = (18.7 × 76.6) + (80 × 4) = 1432 lb. The total weight of engine and tender is 315,000 pounds; subtracting 153,200, the weight on the drivers, we have 161,800, or 80.9 tons, the weight carried by the engine and tender trucks. Item B = (2.6 × 80.9) + (20 × 6) = 330. Item C for velocity M is almost insignificant, say 9 pounds. The sum of A, B, and C is 1771 pounds; subtracting this from 35,174 we have 33,403 pounds, the estimated draw-bar pull for that speed and coal consumption.

To note the effect of increasing the rate of coal consumption, the problem may be again worked through on the basis that the rate of coal consumption is increased, even temporarily, from 4000

pounds to 5000 pounds per hour. The steam developed per pound of coal is reduced from 5.56 to 4.93, but the total steam produced per hour is increased from 22,240 to 24,650. The increased capacity comes through a loss in efficiency. The increased steam production raises the velocity at which full stroke may be maintained from 6.087 m.p.h. to 6.746 m.p.h. and the i.h.p. from 571.0 to 632.8. But the computed cylinder tractive power is practically identical, the numerical computation of 35,174 being only changed to 35,175. But these cylinder tractive powers are each computed for the "*M*" velocities, the maximum velocities at which full stroke can be maintained, and *M* is higher with increased coal consumption. For a real comparison, the figures must be reduced to the same velocity, e.g., the working velocity of 10 m.p.h. $10 \div 6.087 = 1.643$, the multiple for the original problem. For 5000 pounds of coal per hour, *M* velocity is 6.746 m.p.h., and the multiple is 1.482. From Table XXIII we find that the percentages of cylinder tractive power for simple engines for these two multiples of *M* are 77.44 and 81.93, respectively. The higher value is 105.7 per cent of the lower, which shows that, in this case, adding 25 per cent to the rate of coal consumption adds only 5.7 per cent to the cylinder tractive power at 10 m.p.h.

As another instructive variation of the same problem, assume that the coal has effective B.t.u. of 13,000, instead of only 11,700. It will be found that steam will be produced more rapidly, the *M* velocity is 6.777 m.p.h. and the horsepower at that velocity is 635.7, but the cylinder power is computed to be 35,177 pounds, which is again almost identical with the previous values although the *M* velocity is still higher. The multiple for 10 m.p.h. is 1.476 and by Table XXIII the per cent of cylinder tractive power is 82.11, which is an increase of 6 per cent over 74.44 per cent, showing that the increase in effective B.t.u. from 11,700 to 13,000 adds 6 per cent to the cylinder tractive power at 10 m.p.h.

These values for cylinder power may again be checked by the simple rule that

$$\text{Tractive force} = \frac{(\text{piston diameter})^2 \times \text{effective steam pressure} \times \text{stroke}}{\text{diameter of driver}}$$

The "effective steam pressure" is generally considered as 85 per cent of the gage pressure, and for the above case would be

TABLE XXIII*

Per Cent Cylinder Tractive Power for Various Multiples of *M*

(*M* is maximum velocity in miles per hour at which boiler pressure can be maintained with full cut-off)

Velocity	Per Cent (Compound)	Per Cent (Simple)	Velocity	Per Cent (Compound)	Per Cent (Simple)	Velocity	Per Cent (Compound)	Per Cent (Simple)
Start	135.00	106.00	3.6 *M*	32.40	44.75	6.4 *M*		23.59
0.5 *M*	103.00	103.00	3.7 "	31.25	43.56	6.5 "		23.18
1.0 "	100.00	100.00	3.8 "	30.10	42.39	6.6 "		22.79
1.1 "	96.28	95.57	3.9 "	29.14	41.24	6.7 "		22.42
1.2 "	92.55	91.53	4.0 "	28.24	40.10	6.8 "		22.06
1.3 "	88.83	87.83	4.1 "	27.38	39.00	6.9 "		21.71
1.4 "	85.12	84.46	4.2 "	26.56	37.96	7.0 "		21.38
1.5 "	81.40	81.37	4.3 "	25.77	36.97	7.1 "		21.06
1.6 "	77.68	78.55	4.4 "	25.03	36.03	7.2 "		20.75
1.7 "	73.96	75.97	4.5 "	24.34	35.13	7.3 "		20.45
1.8 "	70.25	73.60	4.6 "	23.69	34.26	7.4 "		20.16
1.9 "	66.54	71.41	4.7 "	23.07	33.41	7.5 "		19.88
2.0 "	63.21	69.37	4.8 "	22.48	32.59	7.6 "		19.61
2.1 "	60.20	67.47	4.9 "	21.92	31.82	7.7 "		19.34
2.2 "	57.48	65.67	5.0 "	21.38	31.11	7.8 "		19.08
2.3 "	54.97	63.94	5.1 "	20.87	30.42	7.9 "		18.82
2.4 "	52.68	62.22	5.2 "	20.37	29.75	8.0 "		18.57
2.5 "	50.42	60.55	5.3 "	19.89	29.10	8.1 "		18.33
2.6 "	48.16	58.92	5.4 "	19.43	28.48	8.2 "		18.09
2.7 "	46.08	57.33	5.5 "	18.99	27.87	8.3 "		17.86
2.8 "	44.10	55.78	5.6 "		27.33	8.4 "		17.64
2.9 "	42.29	54.26	5.7 "		26.81	8.5 "		17.43
3.0 "	40.57	52.78	5.8 "		26.30	8.6 "		17.22
3.1 "	38.95	51.33	5.9 "		25.81	8.7 "		17.01
3.2 "	37.42	49.91	6.0 "		25.34	8.8 "		16.82
3.3 "	35.98	48.55	6.1 "		24.88	8.9 "		16.63
3.4 "	34.66	47.24	6.2 "		24.44	9.0 "		16.45
3.5 "	33.53	45.97	6.3 "		24.01			

*Table 5 in Economics Section of Manual of American Railway Engineering Association.

.85×175=149 pounds; diameter piston=22 inches; stroke=28 inches; diameter of driver=57 inches. Then the tractive force =35,425 pounds, which is less than 1 per cent in excess of the other values. This rule is more simple as a method of obtaining merely the maximum tractive power at slow velocities, but the previous method, although longer, is preferable, since it computes the critical velocity *M*, and also the tractive force at higher velocities.

191. Tractive Force at Higher Velocities. At higher velocities than *M*, the cylinder power falls off quite rapidly, since the steam

is cut off at part stroke and is used expansively. The proper per cent of cut-off and the number of pounds of steam per i.h.p. are shown in Table XXI. In Table XXI is given the per cent of cylinder tractive power for multiples of M. The table shows, for example, that, for simple engines, the cylinder tractive power is 69.37 per cent of its value for full stroke when the velocity is $2M$ and that when the velocity is increased to $5M$ the tractive power is reduced to 31.11 per cent. Applying this to the above numerical problem, when $M = 6.087$ m.p.h., the cylinder tractive power is reduced to 31.11 per cent of 35,174, or 10,943 pounds, but, since the velocity is five times as great, the horsepower developed is 31.11 per cent $\times 5 = 1.55$ times as great. It should be noted that Table XXIII shows a slight excess of tractive power (6 per cent when starting) for the simple engine. This is due to the fact that with very low velocities the cylinder pressure more nearly equals the full boiler pressure and there is not the usual reduction of about 15 per cent. Also, compound locomotives are operated with all the cylinders using full-pressure steam, which increases their effectiveness at starting about 35 per cent, although at some loss in economy of steam due to compounding. But since the starting resistances are so much greater than the resistances above 5 miles per hour, the extra assistance is very timely.

192. Further Power Calculations. *Illustrative Example.* Continuing the investigation of the Mikado locomotive (see article 190), draw a curve representing its cylinder tractive power for all

Velocity		Cylinder Tractive Power		Locomotive Resistance (pounds)	Draw-Bar Pull (pounds)
(multiples of M)	(miles per hour)	(per cent)	(pounds)		
0.0	0.000	106.00	37,284	1762	35,322
1.0	6.087	100.00	32,174	1771	33,403
1.2	7.304	91.53	32,195	1775	30,420
1.5	9.131	81.37	28,621	1783	26,838
2.0	12.174	69.37	24,400	1799	22,601
3.0	19.261	52.78	18,565	1854	16,711
4.0	24.348	40.10	14,105	1910	12,195
5.0	30.435	31.11	10,943	1993	8,950
6.0	36.522	25.34	8,913	2095	6,828

velocities from 0 to 35 miles per hour. From the numerical example worked out in article 190, we found that the cylinder tractive power for M velocity (6.087 m.p.h.) was 35,174 pounds. From Table XXIII,

the power at starting is 106 per cent of this, or 37,284 pounds, and the change in power is assumed to vary uniformly in that range. By multiplying 35,174 by the various percentages for the various multiples of M, we have the tractive power at the several velocities. These values are plotted in Fig. 160. From Table XXII we find that the locomotive resistance is 1762 pounds for the A and B resistance at all velocities and that the C resistance varies from about 9 pounds at M velocity (6.087 m.p.h.) to about 333 pounds at 6 M velocity. Subtracting these resistances from the computed values of cylinder tractive power, we have the "draw-bar pull" for the various velocities, all as shown in the tabular form. These several values for cylinder power and of draw-bar pull are plotted for the correspond-

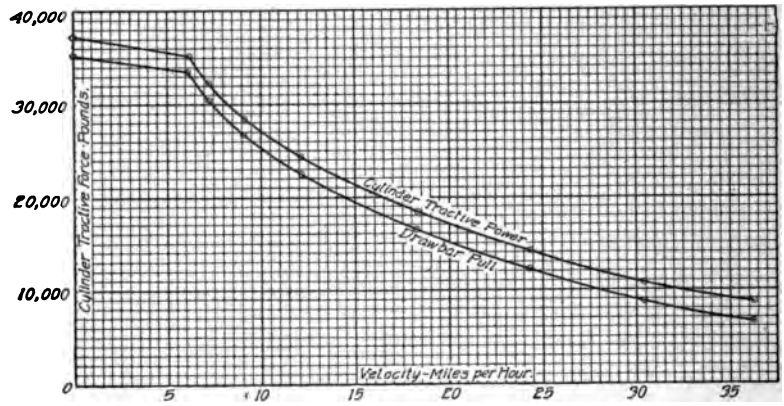

Fig. 160. Tractive Power of Mikado Locomotive at Varying Velocities

ing velocities in Fig. 160, giving the two curves as shown. The rapid decrease in possible draw-bar pull for increase in velocity is well shown. But the student should carefully note that this curve represents the *limitation* of draw-bar pull and not the *actual*, which may be considerably less and which is measured by the resistance.

193. Relation of Boiler Power to Tractive Power. The power at high velocities depends on the rapid production of steam, as has been shown, and this depends on the area of the fire box. All of the older styles of locomotives have fire boxes limited to the width which can be properly placed between the drivers. The Wootten fire box was placed over the drivers, which made it incon-

	Mogul	Prairie
Cylinders, diam. × stroke	20 in. × 26 in.	20 in. × 24 in.
Boiler pressure	200 pounds	200 pounds
Fire box, length × width	108 in. × 33 in.	74 in. × 66 in.
Grate area, square feet	24.70	34.000
Heating surface, sq. ft., fire box and tubes	1952.00	2135.000
Driving wheels, diameter, inches	51.00	51.000
Weight on driving wheels, pounds	137,300.00	122,100.000
Weight of engine alone, pounds	154,000.00	153,300.000
Weight of engine and tender, pounds	254,000.00	253,000.000
Assumed B.t.u. in coal used, 4000 lb. per hr.	12,000.00	12,000.000
Coal per sq. ft. of heating surface per hour	2.05	1.873
Pounds steam per pound coal (Table XIX)	4.16	4.390
Pounds steam per hour (multiply by 4000)	16,640.00	17,560.000
Pounds steam per stroke (Table XX)	2.230	2.058
Pounds steam per revolution (multiply by 4)	8.920	8.232
Revolutions per hour, at *M* velocity	1865.50	2133.500
Revolutions per minute, at *M* velocity	31.09	35.560
Circumference of drivers, linear feet	13.35	13.350
Velocity (*v*), feet per minute, *M* velocity	415.05	474.730
Velocity (*V*), miles per hour, *M* velocity	4.716	5.394
Horsepower at *M* velocity (Table XXI)	434.40	458.400
Cylinder tractive power, pounds, at *M* velocity	31,400.00	31,865.000

veniently high, unless the drivers were objectionably small. Then the plan was devised of placing the fire box over a low pair of trailing wheels and behind the rear pair of drivers. This plan made it possible to double the net width of the fire box. In order to get essential fire-box area in the older styles of locomotives, it is necessary to lengthen the fire box until it is difficult for the fireman to reach and properly clean and tend the fire at the forward end. But by doubling the width, the fire box may be made as large as desired and even shorter than some of the older designs. The

Multiples of *M*	Mogul Locomotive		Prairie Locomotive	
	Velocity (m.p.h.)	Cylinder Tractive Power	Velocity (m.p.h.)	Cylinder Tractive Power
0.0	0.000	33,284	0.000	33,778
1.0	4.716	31,400	5.394	31,865
1.2	5.659	28,740	6.473	29,166
1.5	7.074	25,550	8.091	25,929
2.0	9.432	21,782	10.788	22,105
3.0	14.148	16,573	16.182	16,818
4.0	18.864	12,591	21.576	12,778
5.0	23.580	9,769	26.970	9,913
6.0	28.296	7,957	32.364	8,075
7.0	33.012	6,713		

increased fire-box area justifies a greater heating surface and results in a greater production of steam per pound of coal and a more rapid production of steam, and hence greater power. The value of this change is best shown by a comparison of two locomotives which are very similar in many respects except those due to the difference in fire boxes, etc. The two locomotives are a "Mogul" (2–6–0) and a "Prairie" (2–6–2). The several characteristics, some of which are computed as in article 192, are best shown by tabulating them. (See top of p. 263.)

Knowing the cylinder tractive power at M velocity (M being somewhat different for the two locomotives), we can determine the

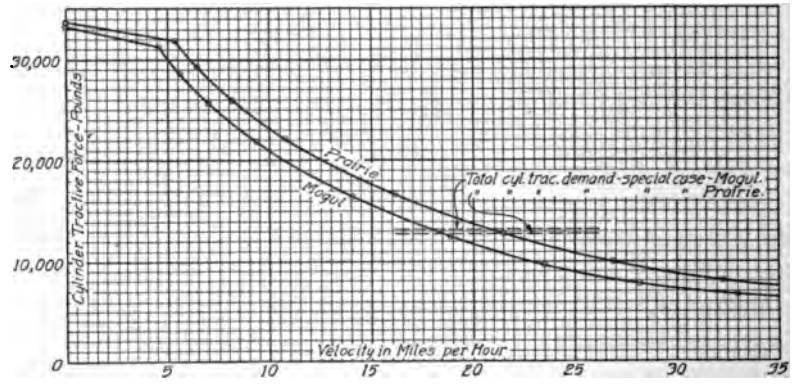

Fig. 161. Comparative Cylinder Tractive Power of Prairie and Mogul Types of Locomotive

cylinder tractive power for various multiples of M, by means of Table XXIII, by the method already given in detail. The results are tabulated at bottom of p. 263 and are plotted in Fig. 161.

The student should note that the two locomotives are of almost the same weight, have the same driving-wheel diameter, same cylinder diameter, same boiler pressure, and are compared on the basis of using the same quality of coal. The Mogul has 15,200 pounds extra on the drivers, which should apparently give it advantage, but Fig. 161 shows that, even at the start, the Mogul has slightly less tractive power. But the Prairie fire box is wider, although shorter, and has 38 per cent more area. This permits more rapid production of steam. By scaling the *vertical* intervals between the two curves at all points, it is found that for any veloc-

ities between 5.5 and 25 miles per hour the Prairie has about 2000 pounds more cylinder tractive power. Of course, the comparison should be made on the basis of their relative draw-bar pulls, which would be obtained by subtracting the engine resistances, as given in Table XXII. But this shows that the engine resistance of the Mogul is greater than that of the Prairie, which leaves an even greater difference in favor of the Prairie.

The trailing wheels under the fire box also serve the purpose of guiding the driving wheels around curves when the locomotive is running backward and in this respect accomplish what the pilot truck does for forward running.

The comparative power of these two locomotives may be shown by a numerical example. Assume that a train of 16 coal cars, each weighing when fully loaded 70 tons, and a caboose weighing 15 tons, is being hauled up a 0.3-per-cent grade at a uniform velocity of about 20 miles per hour. The resistance, by equation (**105**), is

$$R = 2.2 \times (16 \times 70 + 15) + 121.6 \times 17 = 4565 \text{ lb.}$$

The grade resistance of the cars is $20 \times 0.3 \times 1135 = 6810$ pounds. It is assumed that all curve resistance is eliminated by a sufficient reduction of grade where it occurs so that it may be included with the grade resistance. The velocity being assumed uniform, there is no requirement for energy for acceleration. The total car resistance is therefore 11,375 pounds. The engine resistance is a function of the velocity, but considering that the element depending on velocity is relatively small, we will consider it at its average value for 20 miles per hour. The resistances may be computed as 1876 and 1532 for the Mogul and Prairie engines, respectively, which gives 13,251 and 12,907 pounds, respectively, for the total demands on cylinder tractive power. These resistances, being practically independent of velocity, are horizontal lines and are drawn as shown in Fig. 161. This indicates that the limit of velocity of the Mogul locomotive with that train on a 0.3-per-cent grade is less than 18 miles per hour, while the Prairie engine could haul the train at over 21 miles per hour. This gain of 3 miles per hour would have considerable value in the economy of train operation. Or, it may be shown that the Prairie engine could haul 19 loaded cars (an increase of over 18 per cent in revenue load) and a caboose, and

could haul them on the 0.3-per-cent grade at a velocity of 18 miles per hour, the limiting velocity for the Mogul.

The student should remember that, as before intimated, there are several elements of uncertainty (such as the strength and ability of the fireman, and the condition of the track) which might modify the above figures and make them unreliable as a precise measure of the real power of either locomotive, but, on the basis of average conditions, the figures are a measure of the *comparative* value of the two locomotives.

194. Effect of Grade on Tractive Power. The effect of grade on tractive power is best shown by some numerical computations whose results are plotted in Fig. 162. The cylinder tractive power was computed for three engines of greatly different total weight and power, but which had driving-axle loads nearly identical (about 50,750 pounds) and therefore, by the rule given in article 188, could all be operated on the same kind of track. Using the Baldwin Locomotive Works rule, as given in article 188, $\frac{1}{2} \times 50{,}750 \div 300 = 84.5$, which means that the rails should weigh at least 85 pounds per yard. Making computations for these locomotives, using 12,000 B.t.u. coal, similar to those already detailed in articles 190 to 193, it was found that, on a level, the cylinder tractive powers of the Pacific, Mikado, and Mallet locomotives were 29,718, 33,575, 49,095 pounds, respectively, when the velocity was uniformly 10 m.p.h. and the locomotives each burned 4000 pounds of coal per hour. The several engine resistances at 10 m.p.h. are easily computed from Table XXII and are tabulated below. The net values, or the draw-bar pulls, are plotted

Engine Characteristics (At velocity $V = 10$ m.p.h.)	Pacific 4–6–2 (lb.)	Mikado 2–8–2 (lb.)	Mallet 2–8–8–2 (lb.)
Cylinder tractive power on level	29,718	33,575	49,095
Engine resistance on level	2,205	2,648	4,864
Draw-bar pull on level	27,513	30,927	44,231
Draw-bar pull on 3-per-cent grade	15,213	18,207	25,631

on the left-hand vertical line of Fig. 162, and in each case are the left-hand ends of the solid lines which show the tractive powers of the locomotives. On a 3-per-cent grade the grade resistances for the locomotives equal 60 pounds per ton, and are 12,300, 12,720, and 18,600 pounds, respectively. This reduces the effective draw-

bar pull approximately 40 per cent in each case. Since this reduction varies uniformly with the grade, we may plot the three values, 15,213, 18,207, and 25,631, on the 3 per cent vertical line and draw straight lines which represent in each case the tractive power of the locomotive at 10 m.p.h. and on any grade within that range.

Assume trains of cars, all averaging 50 tons per car and varying from 10 cars weighing 500 tons to 50 cars weighing 2500 tons. The resistances at 10 m.p.h. on a level grade are given by equation (105), and may be plotted on the left-hand vertical line of Fig. 162. Grade adds resistance proportional to the grade. For example, on a 0.7-per-cent grade the grade resistance per ton is 14 pounds and for 2500 tons is 35,000 pounds. Adding this to 11,580, the tractive resistance, we have 46,580 which we plot on the 0.7 per cent vertical line. It is indicated by a small circle. Joining the two points gives the resistance line for 2500 tons hauled at 10 m.p.h. The circles on the other lines indicate similar computations. The intersections of these resistance lines with the lines of tractive power indicate the relative power of each locomotive. For example, the 1000-ton train can be hauled by the Pacific locomotive at 10 m.p.h. up a 0.96-per-cent grade, but a Mikado can do the same on a 1.1-per-cent grade, while the Mallet can do it on a 1.52-per-cent grade.

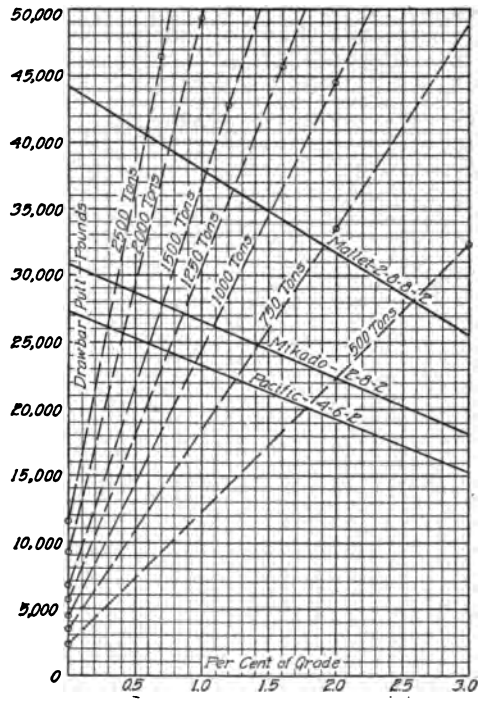

Fig. 162. Curves Showing Effect of Grade on Tractive Power

All of these calculations were made on the basis of burning 4000 pounds of coal per hour, which, as before stated, is the

practical limit of what an ordinary fireman can be expected to do for an extended run.

The description of the Mallet locomotive (built by the Baldwin Locomotive Works) stated that its tractive power is 91,000 pounds. A computation of its cylinder tractive power at *M* velocity, using 12,000 B.t.u. coal, shows it to be 95,389 pounds. Subtracting the engine resistance (4843 pounds) we would have 90,546 pounds, which is a very fair check, especially as the Baldwin Locomotive Works method of calculation is different.

195. Acceleration—Speed Curves. The time required for an engine of given weight and power to haul a train of known weight and resistance over a track with known grades and curvature is an important and necessary matter for an engineer to compute, since the saving in time has such a value as to justify constructive or operating changes which will reduce that time. Fig. 160 shows that the draw-bar pull is very much greater at very low velocities than at the moderate speed of even 15 m.p.h. In spite of the increased resistance at these low velocities the margin of power left for acceleration is also greater and the "speed curve" is really a curve and not a straight line. Its general form may be most easily developed by a numerical example, especially as each case has its own special curve.

Illustrative Example. The Mikado locomotive, whose characteristics have already been investigated in article 190 *et seq.*, has draw-bar pulls at various velocities as shown in the tabular form in article 192, to which frequent reference must be made in this demonstration. Assume that this locomotive starts from rest on a 0.4-per-cent upgrade, hauling a train of 14 cars, each weighing 50 tons, and a caboose weighing 10 tons. Then the normal level tractive resistance, by equation (105), equals

$$R = (2.2 \times 710) + (121.6 \times 15) = 3386 \text{ lb.}$$

The grade resistance of the cars will be $20 \times 0.4 \times 710 = 5680$ pounds. The extra starting resistance will be considered as 6 pounds per ton, or 4260 pounds. These three items total 13,326 pounds. The average draw-bar pull of the locomotive at velocities between zero and *M* velocity, which is 6.087 m.p.h., is 34,362 pounds, but this must be diminished in this case by $20 \times 0.4 \times 157.5 = 1260$

pounds for grade and by $157.5 \times 6 = 945$ pounds for starting resistance, leaving a net draw-bar pull of 32,157 pounds, excluding the force required for the acceleration of the locomotive. The net force available for acceleration of both the locomotive and the train is $32,157 - 13,326 = 18,831$ pounds, or prorated, is $18,831 \div (157.5 + 710) = 21.71$ pounds per ton. Transposing equation (104), with $V_1 = 0$, $V_2 = 6.087$, and $P = 21.71$ pounds, we have $s = (37.05 - 0) 70 \div 21.71 = 119$ feet, the distance required to attain a velocity of 6.087 m.p.h.

While the velocity is increasing from 1.0 M to 1.2 M, the mean draw-bar pull is $31,912 - 1260 = 30,652$ pounds, less the accelerative resistance of the locomotive. Subtracting the tractive and grade resistances of the cars, we have $30,652 - 3386 - 5680 = 21,586$ pounds. Note that there is no longer any starting resistance. The accelerative force in pounds per ton is $21,586 \div 867.5 = 24.88$. The distance s required to increase the velocity from 6.087 m.p.h. to 7.304 m.p.h., is $(53.35 - 37.05)70 \div 24.88 = 46$ feet. Similarly the distances required to increase the velocity from 1.2 M to 1.5 M, from 1.5 M to 2 M, etc., are computed as in the accompanying tabular form, p. 270.

The corresponding distances and velocities have been plotted in Fig. 163. The velocity of 10 m.p.h. is acquired in a little over 300 feet, but it requires nearly 1000 feet to acquire a velocity of 15 m.p.h. and about 2400 feet to raise it to 20 m.p.h. The force, in pounds per ton, available for acceleration is maximum at low velocities, after the extra starting resistance is overcome. As the margin per ton for acceleration becomes less and less, the greater is the distance required to increase the velocity 1 mile per hour—especially through the last increments—up to the velocity at which the net draw-bar pull exactly equals the total car resistance and the velocity becomes uniform. There is an approximation in using *average* draw-bar pulls between the different velocities at which the draw-bar pull has been definitely computed, but the computed distances are practically correct up to 4 M velocity or 24.35 m.p.h. But the computation for the distance required to increase the velocity from 4 M up to 4.58 M is far less accurate if the average draw-bar pull is used. The effective pull at 4 M velocity equals $12,195 - 1260 = 10,935$, less the accelerative resist-

Velocities				Tractive Forces						Distances		Time
(Ft. per sec.)	Range (mi. per hr.)		Mean (ft. per (sec.)	Mean Draw-Bar Pull, Level (lb.)	Locomotive Resistance Grade Plus Start* (lb.)	Actual Draw-Bar Pull Average (lb.)	Car Resistance Tractive, Grade Plus Start* (lb.)	Difference Available for Acceleration (lb.)	Net Force, per Ton (lb.)	Accelerative s (ft.)	Total from Start (ft.)	(Sec.)
0.00	0.00	6.087	4.47	34,362	*2,205	32,157	*13,326	18,831	21.71	119	119	27
8.94	6.087	7.304	9.75	31,912	1,260	30,652	9,066	21,586	24.88	46	165	5
10.57	7.304	9.131	12.00	28,629	1,260	27,369	9,066	18,303	21.10	100	265	8
13.41	9.131	12.17	15.63	24,720	1,260	23,460	9,066	14,394	16.59	274	539	18
17.85	12.17	19.26	23.05	19,656	1,260	18,396	9,066	9,330	10.76	1,452	1,991	63
28.25	19.26	24.35	32.00	14,453	1,260	13,193	9,066	4,127	4.76	3,262	5,253	102
35.76	24.35	27.88	38.33	.....	.....	.....	.....	935	.....	11,981	17,234	312

*The extra starting resistance only applies to the first item.

ance of the locomotive. The tractive and grade resistance of the cars at this velocity is 3386+5680=9066. This leaves 10,935−9066=1865 pounds available for acceleration of both locomotive and cars. The reduction in tractive force between $4M$ velocity and $5M$ velocity (see article 192) is 12,195−8950=3245 pounds. By proportionate interpolation we would then say that the excess force available for acceleration would be exhausted at (1869÷3245) =.58 of the interval, or at a velocity of 4.58 M, or 27.88 m.p.h. The mean accelerative force is one-half of 1869, or 935 pounds, which is 1.077 pounds per ton of train. The distance, by an inver-

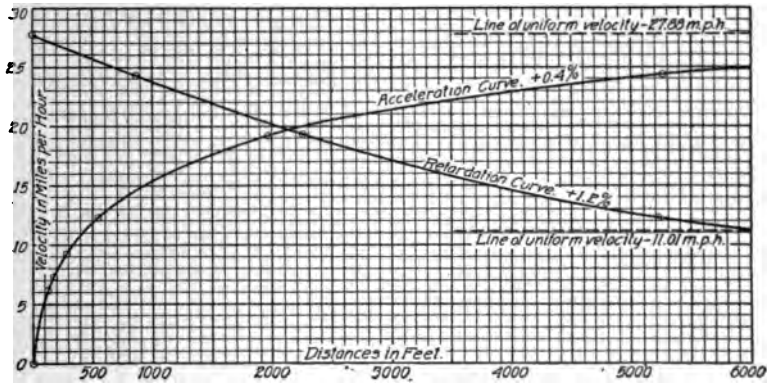

Fig. 163. Time Curves for Mikado Locomotive and Train

sion of equation (104), is computed to be 11,981 feet. Owing to the approximate equality of working force and resistance and the momentary variations in both, the precise point where the acceleration would cease and the velocity would actually become uniform would be very uncertain. Fortunately the inaccuracy is of little or no practical importance and for the purposes of our calculations we may call this last interval 11,981 feet, assuming that the grade is as long as 17,234 feet or 3.2 miles. If the 0.4-per-cent grade continued indefinitely the train would travel at this uniform velocity as long as the locomotive operated on the basis assumed for this problem. Note that Fig. 163 would have to be extended to nearly three times its present length before the time curve would reach and become tangent to the "line of uniform velocity".

Velocities			Tractive Forces					Distances		Time
(Ft. per sec.)	Range (mi. per hr.)	Mean (ft. per sec.)	Mean Draw-Bar Pull, Level (lb.)	Locomotive Resistance Grade (lb.)	Actual Draw-Bar Pull Average (lb.)	Car Resistance Tractive and Grade (lb.)	Difference Effective for Retardation (lb.)	Net Force per Ton (lb.)	Accelerative s (ft.)	Total from Start (ft.)	(Sec.)
40.89	27.88 24.35	38.33	11,260	3,780	7,480	20,426	12,946	14.92	863	863	23
35.76	24.35 19.26	32.00	14,453	3,780	10,673	20,426	9,753	11.24	1,382	2,245	70
28.25	19.26 12.17	23.05	19,656	3,780	15,876	20,426	4,550	5.24	2,975	5,220	129
17.85	12.17 11.01	17.00	.....	.....	.....	.....	1,316	1.517	1,246	6,466	73

196. Retardation—Speed Curves. When, on account of grade resistance, the total of tractive and grade resistance is greater than the draw-bar pull, there is retardation.

Illustrative Example. Continuing the numerical problem of article 195, assume that, while moving up the 0.4-per-cent grade at a velocity of $4.58M$, or 27.88 m.p.h., the train reaches a grade of +1.2 per cent. The grade resistance of the cars will be $20 \times 1.2 \times 710 = 17{,}040$ pounds. The tractive resistance will be 3386 pounds, as before, making a total of 20,426 pounds. Interpolating in the tabular form in article 192 for the draw-bar pull at $4.58M$ velocity, we find 10,326; at $4M$ it is 12,195, and the mean is 11,260; but from this must be subtracted $20 \times 1.2 \times 157.5 = 3780$ for grade resistance of the locomotive, leaving 7480 pounds for the net draw-bar pull. The retarding force is $20{,}426 - 7480 = 12{,}946$; or in pounds per ton of train, is $12{,}946 \div 867.5 = 14.92$. As before, using an inversion of equation (104), $s = (777 - 593)70 \div 14.92 = 863$ feet, the distance at which the velocity would reduce to $4M$. As before, the other quantities may be computed

and recorded, with less danger of confusion and error, by tabulating them, as given on p. 272.

The mean velocity, when retarding from $4.58\,M$ to $4.0\,M$, reduced to feet per second, is as before 38.33 feet per second, and dividing this into the distance, 863 feet, gives 23, the time in seconds. The quantities for the reduction in velocity from $4\,M$ to $3\,M$ and from $3\,M$ to $2\,M$ are computed similarly. The level draw-bar pull for $1.5\,M$ is 26,838 (see article 192) and by subtracting 3780, we get 23,058 pounds the actual net pull on the grade. Similarly, the actual pull at $2\,M$ is 18,821 pounds. The increase from 18,821 to 20,426 is $\frac{1605}{4237}=38$ per cent of the interval from 18,821 to 23,058 and 38 per cent $\times .5=.19$; therefore, the actual draw-bar pull just equals the resistance at $2.0-.19=1.81\,M$, or 11.01 m.p.h. The excess draw-bar pull at $2.0\,M=23{,}058-20{,}426=2632$ pounds. At $1.81\,M$ the excess is zero and therefore the mean excess is one-half of 2632, or 1316. Dividing this by 867.5, we have 1.517, which is the value of P in equation (104). Then

$$s=(148.2-121.2)70\div 1.517=1246 \text{ ft.}$$

Velocities in miles per hour can be readily converted into velocities in feet per second by multiplying by 1.4667. Averaging the two velocities at the beginning and the end of each period gives the mean velocity; and dividing each of these into the distance for that period gives the time in seconds.

197. Drifting. The tractive resistance of the cars of the problem just worked out is 3386 pounds; the locomotive resistance at 20 m.p.h. is 1862 pounds, or a total of 5248 pounds. Variation in velocity will affect this but little. Dividing by 867.5, the total weight in tons, we have 6.05 pounds, the resistance per ton, from which the equivalent rate of grade is $6.05\div 20=.302$ per cent. This means practically that when this train is running *down* a grade which is over .302 per cent it will run by gravity and steam may be shut off. If the grade is much greater than .302 per cent the acceleration on the downgrade may become so great, if the grade is very long, that the velocity may become objectionably high.

Illustrative Example. Assume that the limiting safe velocity for freight trains, considering the condition of track and rolling

stock, is 40 m.p.h.; assume that the train we have been considering reaches a 0.4-per-cent downgrade at a velocity of 15 m.p.h. How far down the grade will it run with steam shut off, before the speed reaches 40 m.p.h. and brakes must be applied? There is no question here of variable tractive power since the only motive power is gravity. The resistance is nearly independent of velocity and we will here assume it to be so and utilize Table XVII. At 15 m.p.h. the train has a velocity head of 7.90 feet. At 40 m.p.h. the velocity head is 56.19 feet. The train can therefore drop down the grade a vertical height of $56.19-7.90=48.29$ feet before the velocity reaches 40 m.p.h. On a 0.4-per-cent grade the distance required for such a fall is $48.29\div.004=12{,}072$ feet. The problem in article 195 assumed that the 0.4-per-cent grade is 17,234 feet or more, and this shows what will happen to the trains moving in the opposite direction.

But it must not be thought that there is no loss of energy during drifting. Even though no steam is used in the cylinders, some is frequently wasted at the safety valve and more is used in operating brakes and in maintaining the brake air reservoir at full pressure. But the greatest loss of heat is that due to radiation, especially in winter, in spite of all the jacketing devices to retain heat. Although the results of the numerous tests which have been made are quite variable, the following approximate averages may be used: the loss due to radiation while standing may be figured as 120 pounds of coal per hour per 1000 square feet of heating surface; while drifting the loss will increase to 220 pounds per hour. The amount of coal used for firing up will be about 510. This is based on the use of 12,000 B.t.u. coal. The better the coal, the less will be used.

Illustrative Example. The Mikado locomotive we have been considering has 2565 square feet of heating surface. It will then require about $2.565\times510=1308$ pounds of coal to fire up. While drifting down the grade, referred to above, a distance of 12,072 feet, the average velocity is $\frac{1}{2}(15+40)=27.5$ m.p.h. $=40.3$ ft. per sec. and the required time is $12{,}072\div40.3=300$ seconds $=5$ minutes $=.083$ hour. The coal used while drifting down this short run would be

$$220\times2.565\times.083=47 \text{ lb.}$$

At this point brakes would need to be applied and the time spent in drifting beyond this point must be computed as an item in the total time spent on the run and also to compute the total amount of coal consumed while drifting. Although this item of 47 pounds is relatively very small, its method of computation is typical of the computation of the several items to make up the total of coal consumed during a trip.

198. Review of Computed Power of One Locomotive. It was assumed that it started on a +0.4-per-cent grade with a load of 15 cars weighing 710 tons. After moving 17,234 feet (assuming that the grade was that long) and doing it in 535 seconds, or 8 minutes 55 seconds, the train acquired a velocity of 27.88 m.p.h. and the power of the locomotive would then be sufficient, when burning 4000 pounds of coal per hour, to keep it moving up such a grade indefinitely at that velocity. In case the grade were not as long as 17,234 feet, it would be necessary to compute the velocity where the rate of grade changed and make that the basis for the computation on the succeeding grade. But, assuming that the grade were as long as 17,234 feet, or more, and that the velocity of 27.88 m.p.h. had been acquired, and that the train had run at that speed for some distance—although this does not modify the problem—the train is assumed to reach a still steeper grade, +1.2 per cent. The velocity then begins to decrease and in a total distance of 6466 feet and a total time of 295 seconds, or 4 minutes 55 seconds, the velocity is reduced to 11.01 m.p.h. at which velocity the locomotive is able to make steam fast enough to overcome the higher resistance on the steeper grade. From that point on, assuming that the 1.2-per-cent grade is longer than 6466 feet, the train would continue for the remaining length of that grade at the velocity of 11.01 m.p.h.

As before stated, precision in the above results depends on many factors (such as B.t.u. of coal used, or the actual consumption in pounds per hour) which are somewhat variable. Sometimes the variation of these factors from the values used above is known; sometimes it is unknown and then the accuracy of the results is correspondingly uncertain. But whether accurately known or not, when this method is used, employing the best values for the factors which are obtainable, the method shows a valuable *comparison* of two proposed alinements or grades. In such a com-

parison, any error in the factors will affect both results nearly, if not equally, and the comparative results will still be substantially correct.

199. Selection of Route. The preceding articles may be utilized in comparing two routes. If one of the lines is already in operation, the engineer has the great advantage of being able to determine by test exactly what results may be obtained on that line and what factors should be used in computations. It is then only necessary to compute the quantities for the proposed new line. When both lines are "on paper" there is less certainty as to the accuracy of the results, except that the line which is shown to be most advantageous will probably continue to be most advantageous even if the uncertain factors used in the comparison are somewhat changed. Using the methods outlined in articles 195 to 197, there will be computed the behavior of an assumed type of locomotive, hauling one or more types of train load, and passing over tracks having definite grades and lengths. The effect of curves may be disregarded provided that the grades were properly compensated during original construction, and then the rate of grade for the entire length of straight and curved track may be taken as the rate on the straight track. If the rate of grade is actually uniform, even through the curves, then the lengths of curved track must be computed separately and on the basis of a rate of grade equal to the actual rate plus an allowance of .035 per cent for each degree of curve. The behavior of a train from starting to stopping must be computed, making due allowance for each change in condition which will affect the hauling power of the locomotive. The locomotive is assumed to be working at the limit of its steaming capacity, except when drifting with steam shut off on a downgrade, or when brakes are applied, either to prevent objectionably high velocity on a downgrade or to make a stop. The action of brakes during a service stop (as distinguished from an emergency stop) may be considered as a retarding force varying from 10 per cent to 20 per cent of the train weight. Unfortunately brake action is so variable, being directly under the control of the locomotive engineer and varying from zero to the full braking power, that any computation of energy used in operating them or of the effect of the brakes is impracticable except on the basis of arbitrary assumptions such

as the requirement that the brakes are used in such a way that a train will be retarded at a specified rate. The performance of the locomotive over the entire division, the total time required, its velocity in critical places, etc., can be computed. In articles 195 and 196 it was shown that the locomotive considered could haul the particular train considered up a 0.4-per-cent grade at a velocity of 27.88 m.p.h. and maintain such speed indefinitely; also that it could haul the same train up a 1.2-per-cent grade at 11.01 m.p.h. and maintain its velocity indefinitely. This of course means that a much heavier train could be hauled up the 0.4-per-cent grade and that a somewhat heavier train could be hauled up the 1.2-per-cent grade without being stalled, although the velocities in each case would be reduced. There are an infinite number of combinations but there are usually some considerations which narrow the choice. Even after construction is complete these tables may be utilized in a study of the most economical combination of type of locomotive and amount of train load for the track conditions as they may exist.

PUSHER GRADES

200. General Principles of Economy. It frequently happens that the natural line of a road includes a few grades which are considerably higher than all other grades. These higher grades may be practically hopeless, because a material reduction in them would cost more than it is worth, or more than the general financial condition of the road can afford. A common error is to consider such a grade as the ruling grade and then recklessly permit, at any other place on the road, the adoption of any grade less than this on the ground that it could never limit the operation of trains. But in such cases, it *may* be easily practicable to operate the higher grades with a pusher engine and cut down all lesser grades to such a rate of grade that the "through" engine can haul as many cars on them as two engines can haul on a pusher grade. The economy underlying the method may be seen by a simple illustration which is freed from all details.

Assume that on a division 100 miles long there are two grades of 5 miles each on which pusher engines are to be used; assume that the grades on the other 90 miles are so low that one engine

may haul as many cars on them as two engines can haul on the pusher grades; then by using pusher engines the weight of all heavy trains may be doubled and the heavy freight may be handled in half as many trains. But this economy is effected at the cost of operating the pusher engines. Using single engines for the whole trip, it will require 200 engine-miles to haul a double load. But a single engine can haul the double load over 90 miles of the run, and the same engine with one pusher can haul it up the heavy grades. Each pusher engine will travel 10 miles on each grade, or 20 miles for the two, and the total number of engine-miles for a double load will be 120, instead of 200. And when it is considered that the cost of a pusher engine-mile is far less than that of an ordinary train-mile, as will be shown, the advantages of the method are still more marked.

Of course the full economy of the method is only realized when the maximum *through* grade bears its proper relation to the pusher grade. If the maximum through grade is greater than its proper corresponding value for the pusher grade, then the number of cars is limited by that through grade and the power of the pusher engine is not completely utilized on the pusher grade. Economy of operation requires that an engine should work nearly to the limit of its capacity for as large a portion of the time as possible, and therefore when a heavy engine is compelled to haul a light train over nine-tenths of the route in order that there shall be sufficient power on the other tenth, where alone it is needed, it indicates a lack of economy in the design. It now becomes necessary to develop the proper relation between through and pusher grades.

201. Balance of Grades for Pusher Service. *Illustrative Example.* This will be easiest understood by a numerical problem. Suppose that at two or three places on the line it seems impracticable to obtain at a reasonable expense a grade less than 2.10 per cent (nearly 111 feet per mile). But since it seems practicable to make a very much lower grade elsewhere, we will compute the corresponding through grade as the grade to work for. Assume that the through and pusher engines are alike and that, for simplicity in calculation, they are of the Mikado type and of the particular dimensions whose characteristics have already been developed in article 190 *et seq.* The draw-bar pull at M velocity (6.087

m.p.h.) is 33,403 pounds. But on a 2.10-per-cent grade this must be diminished by $20 \times 2.10 \times 157.5 = 6615$ pounds, the grade resistance. Two such engines on the 2.10-per-cent grade would have a total net draw-bar pull of 53,576 pounds. Assume that the trains to be hauled are made up entirely of coal cars, fully loaded to 100,000 pounds, and weighing 40,000 pounds, and also a caboose weighing 12 tons. On the basis of equation (105), the tractive resistance of each coal car is 275.6 pounds and that of the caboose 148 pounds. On the 2.10-per-cent grade the total resistance would be 3215.6 pounds for each coal car and 652 pounds for the caboose. The net pull available for coal cars is $53,576 - 652 = 52,924$ pounds, from which $52,924 \div 3215.6 = 16+$, showing that 16 loaded coal cars, besides the caboose, could be hauled up the 2.10-per-cent grade by the two locomotives, and that there would be a considerable margin of tractive power. We must determine the rate of grade on which one locomotive, with a cylinder tractive power of 35,174 pounds at M velocity (6.087 m.p.h.), can haul a load of 157.5 tons (engine) plus 16×70, or 1120 tons (coal cars) plus 12 tons (caboose), or a total of 1289.5 tons. The tractive resistance of the locomotive (see article 190) is 1771 pounds; for the cars it is $275.6 \times 16 + 148 = 4558$ pounds, or a total for the whole train of 6329 pounds. The force available for grade is $35,174 - 6329 = 28,845$ pounds, and $28,845 \div 1289.5 = 22.4$ pounds per ton, which is the grade resistance on a 1.12-per-cent grade. The net result of the above calculation is that the proposed road may be constructed with 2.10-per-cent grades as pusher grades, provided that the ruling grade for single engines is kept as low as 1.12 per cent.

Sometimes, though rarely, two pusher engines, and even three, may be used on a pusher grade. This might be found desirable on the basis of a combination of grades on each of which the resistance is such that one uniform train load can be handled with the same facility by one engine (or two, or three, or even four). Although the calculations are more complex, they are worked on precisely the same principles as those used above.

202. Operation of Pusher Engines. Economy in pusher-engine work demands that the schedule of trains be so arranged that the pusher engine can be kept constantly at work. If there are several short pusher grades separated by several miles of level

track, it means either that a pusher engine must be assigned to each grade, where there may not be enough work to keep it busy, and therefore its daily cost divided by its engine-mileage is abnormally large, or else it must travel uselessly over some intervening stretches of level track in order to be at hand when wanted. Even the time table of the trains must be arranged with reference to the pusher service so that there will not be an accumulation of traffic at the pusher grades at certain hours, with nothing to do at other times. The locating engineer has no concern with the operation of trains, but he should bunch the pusher grades if possible, even spending a little additional money for it if necessary.

On very light-traffic roads, where the trains are so few that the method does not interfere with the schedule, a pusher grade may be operated by a single engine, by taking half of the train up first, leaving it on a switch, and then returning after the other half. This means slow time (which a very poor road can afford); it means a saving of the cost of the extra engine, and also the comparatively costly maintenance of it if the total amount of pusher work is very light. Such a road is probably not blessed with an excess of traffic except during a small part of the year, and the cost and maintenance of a useless pusher for a large part of the year is thereby saved. But it should be noted that even if it is expected to follow this policy, it does not make the slightest difference in the design of the pusher grades or in the ratio of through to pusher grades.

Another possible method of economizing on pusher service, especially on light-traffic roads, where a pusher grade begins or ends near a station yard which is so large that a switching engine is necessary for at least part of the day, is to combine the switching and pusher work. A little ingenuity in planning the schedule will thus enable the pusher engine to utilize its whole time in useful work.

203. Length of Pusher Grade. The true length which must be considered in the following calculations is always somewhat in excess of the length of the actual grade as measured on the profile. Although it is sometimes possible, by having the pusher engine approach the train from behind, to accomplish its work without stopping the train either at the top or bottom of the grade, yet

this requires an extra length of track and considerable extra mileage on the part of the pusher engine. For passenger service the assistant engine is always placed in front, and although it is practicable to uncouple the assistant engine at the top of the grade, run it ahead at increased speed, run it on a siding and again clear the main track without stopping the train, it is usually necessary to stop the train at the bottom to couple on. Increased mileage is necessary for this. The stoppage and restarting of a heavy train uses up as much energy as would carry the train several miles on a level track and therefore an increased run by the pusher engine is justifiable if it will save stopping the train. A siding at or near the bottom and top of the grade (and also a telegraph office) is a convenience and almost a necessity for the quick and safe operation of pusher grades, and while they must be clear of the grade it is sometimes more convenient to remove them some distance from the ends of the grade. Each case is a separate problem, but the length to be used in the following calculations must always be the actual run of the pusher engine, which will be somewhat in excess of the actual length of the pusher grade as shown on the profile.

204. Cost of Pusher-Engine Service. The cost depends partly on the work done by the engine and partly on mere time. The wages of the enginemen must be paid on a *per diem* basis rather than on a mileage basis, and if the engine does not run many revenue miles, the cost for the miles it does run is increased. In view of the fact that the damage to roadway and track by a locomotive has been estimated to be 2 to 4 times that due to an equal weight of cars, it is evidently approximately true that pusher engines, which are usually of the heavy-freight type, should be charged about the same as the average charge for all trains, for all the items of maintenance of way. According to Table XVI, this should be about 18 per cent of the average cost of a train-mile. Adding the full percentage for engine repairs, fuel, water, lubricants and supplies, signaling and telegraph, but excluding enginemen's wages, we have, according to the figures for 1912, a total of about 40 per cent of the average cost of a train-mile. To this must be added the full *per diem* charge for wages of enginemen and firemen. In 1912, this averaged for the whole United States $5 per day for enginemen and $3.02 for firemen, but considering that there has

been an almost uniform increase in these figures from $3.84 and $2.20, respectively, since 1902, their values during the next few years are problematical and must be determined for each individual case. There must also be added a charge for the capital cost of the engine. Since the cost of repairs and maintenance has already been included, the initial cost divided by the estimated number of miles in its total mileage life gives a charge per mile which covers the capital cost. If such an engine costs $20,000 and its mileage life is 800,000 miles, the capital cost per mile is 2.5 cents. But since the pusher engine must run 2 miles for each mile of pusher grade, we must multiply the above computed mileage charge by 2 for each mile of pusher grade.

Illustrative Examdle. A locating engineer may find himself compelled to choose between two policies, which may be illustrated as follows: Resuming the numerical case of article 201, assume that the engineer finds that he can concentrate grading expenditures on certain parts of the line and make a through grade with a maximum of 1.5 per cent, or he can concentrate on other parts of the line and cut down all single-engine grades to 1.12 per cent, leaving two grades of 2.1 per cent whose *effective* pusher-grade lengths (see article 203) are 7 and 8 miles, respectively. Assume that the two methods may be constructed for about equal cost. Which is preferable?

From the calculations of article 201, we find that the drawbar pull at M velocity on a level is 33,403 pounds and on the 1.5-per-cent grade it is $20\times1.5\times157.5=4725$ pounds less, or 28,678 pounds. The tractive and grade resistance of the caboose is $148+(20\times1.5\times12)=508$ pounds, and $28,678-508=28,170$ is the force available for the coal cars. The resistance of each car is $276+(20\times1.5\times70)=2376$ pounds, and $28,170\div2376=11.8$, showing that one such locomotive would be hardly capable, unless by extra forcing, to haul even 12 cars up the ruling 1.5-per-cent grades. The calculations of article 201 show that the revenue train load for the combination of 1.12 per cent through grade and 2.1-per-cent pusher grade is 16 loaded coal cars. Of course the other kinds of traffic should also be considered; but if the passenger traffic were very light and there were only a very few cars per train, it might make no difference, beyond a comparatively harmless reduc-

tion in velocity for a few minutes each and at a few points, whether the grade is 1.5 per cent or 2.1 per cent. For simplicity we will confine the problem to a comparison of these grades on the basis of trains of loaded coal cars. Assume that the division is 100 miles long and that there is a traffic against these grades of 96 carloads of coal per day. For simplicity we ignore all traffic in the other direction. The effect of other details, for or against, must be computed separately and independently. With pusher-engine grades the traffic can be handled in 6 trains; on the 1.5 per cent through grades, it will require 8 trains (or 9). On the 7-mile pusher grade there will be 14 pusher-engine-miles per trip; on the other grade, 16. Then the two pusher engines must run 84 and 96 miles, respectively, per day. Suppose that the average cost of a train-mile on that road is $1.60 and that we estimate 40 per cent of it, or 64 cents, as the charge per pusher-engine-mile for maintenance of way, engine repairs, fuel, etc. Suppose that the pusher engines cost $16,000 and that the mileage charge for capital cost is 2 cents. Assume for wages of enginemen, $5, and for firemen, $3. Then the daily charge for one engine is

$$84\ (0.64+0.02)+5.00+3.00=\$63.44$$

and for the other engine

$$96\ (0.64+0.02)+5.00+3.00=\$71.36$$

It should be noted that only the charges for wages, repairs, and supplies will be directly apparent. A considerable proportion of the above cost is that due to track maintenance, which is a proper charge but it may be forgotten. The proper mileage cost for through-freight trains, operated at the limit of their capacity, is evidently much greater than that of the *average* train. Assume that the cost of these through-freight trains has been computed as $2.20 per mile for that road, as against $1.60 per mile for the average train. Then the comparative costs of the two systems would be:

On 1.5 per cent through grade:		On 1.12 per cent through grade, 2.1 per cent pusher grade:	
8 trains at $2.20 per mile, for 100 miles, per day	$1760	6 trains at $2.20 per mile for 100 miles, per day	$1320
		1 pusher engine (84 miles)	63
		1 pusher engine (96 miles)	[illegible]
	$1760		$1

If 9 trains, instead of 8, were necessary to haul the traffic, the advantage in favor of the pusher grade would be still greater. On the other hand, each of the 6 trains on the pusher-grade line is heavier than one of the 8 trains of the 1.5 per cent line and therefore we might expect greater injury to the track and that a greater charge for track maintenance or a larger total expense per train-mile would be charged. But, as before stated, the locomotive does the larger part of the damage and the addition of cars makes but little difference. The saving of $306 per day, or $95,778 for 313 working days per year, is equivalent, if capitalized at 5 per cent, to a capital expenditure of $1,915,560. This sum, so far as it is accurate, represents the extra expenditure, if necessary, which would be justified to adopt the pusher-grade plan rather than the other.

BALANCE OF GRADES FOR UNEQUAL TRAFFIC

205. Fundamental Principles. The volumes or weights of the traffic in each of the two directions on any road are usually quite different and frequently that in one direction is 4 or 5 times that in the other. The number of through engines passing over the road in each direction each day is necessarily equal, and, unless some engines run "light", the number of trains must be the same. The number of passenger cars must be the same, and, in the long run, even the number of freight cars must be the same. But if the weight of the freight is very largely greater in one direction than in the other, the cars will run nearly or quite full in one direction and nearly or quite empty in the other direction. The lightly loaded trains will therefore weigh less, and, with the same through engine, can surmount a steeper grade than the heavily loaded train. It therefore becomes justifiable to introduce a slightly heavier grade against the lighter traffic, if economy of construction is thereby obtained.

There are many roads which are not concerned with this phase of grade. When a branch line runs to some terminus in the mountains so that practically all of the heavy grades are in one direction and there are no opposing grades when running out of the mountains (barring a few harmless sags), there is no limitation of trains by grades except in the one direction, and there is

no necessity or object in computing any balance. But the through-trunk lines, especially those running east and west, find that their east-bound traffic is 3 or 4 times their west-bound traffic.

As a single instance, from 1875 to 1880, the ratio of the east-bound ton-mileage to the west-bound on the Pennsylvania railroad was more than 4.5 : 1. The difference of elevation of the terminals has little or no importance in this case since it is so small compared with the total length of the line, and since any possible effect which it might have had on the grade is utterly lost in the heavy grades in both directions when crossing the mountains. Admitting the justification of a variation in the ruling grade in opposite directions so as to produce a virtual equality in tractive effort, it now becomes necessary to compute the theoretical balance.

206. Computation of Theoretical Balance. In spite of the very evident disparity in the weight of the freight traffic in the two directions, there are some equalizing factors, as will be shown:

(1) The locomotive and passenger-car traffic in the two directions are equal.

(2) The passenger traffic in the two directions will be equal. There is a slight exception to this when a road handles a considerable number of emigrants, but the effect of this is absolutely insignificant, especially in view of the further fact that the ratio of dead load to live load is very high with passenger traffic. Considering that even 50 passengers in a car, assumed to weigh 150 pounds apiece, would only weigh 7500 pounds which is but one-sixth of the 45,000 pounds which the car probably weighs, even a considerable variation in passenger traffic each way would not affect the gross load materially.

(3) Empty cars have a greater resistance per ton than loaded cars. The difference may amount to about 4 pounds per ton. Therefore, although a train of loaded cars will require a greater gross tractive effort than an equal number of empty cars, the ratio will not be in proportion to the gross tonnage.

(4) In spite of the best care and regulations on the part of the traffic department, many freight cars will run in the direction of the heaviest traffic either empty or but partly loaded.

(5) In general it is the freight which has the greatest bulk and weight, such as grain, coal, lumber, ore, etc., which is

If 9 trains, instead of 8, were necessary to haul the traffic, the advantage in favor of the pusher grade would be still greater. On the other hand, each of the 6 trains on the pusher-grade line is heavier than one of the 8 trains of the 1.5 per cent line and therefore we might expect greater injury to the track and that a greater charge for track maintenance or a larger total expense per train-mile would be charged. But, as before stated, the locomotive does the larger part of the damage and the addition of cars makes but little difference. The saving of $306 per day, or $95,778 for 313 working days per year, is equivalent, if capitalized at 5 per cent, to a capital expenditure of $1,915,560. This sum, so far as it is accurate, represents the extra expenditure, if necessary, which would be justified to adopt the pusher-grade plan rather than the other.

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(4) In spite of the best care and regulations on the part of the traffic department, many freight cars will run in the direction of the heaviest traffic either empty or but partly loaded.

(5) In general it is the freight which has the greatest bulk and weight, such as grain, coal, lumber, ore, etc., which is

run from the rural districts toward the cities and manufacturing districts.

(6) The return traffic, which consists chiefly of manufactured products, and which is worth as much as the other, weighs but a small fraction of the other.

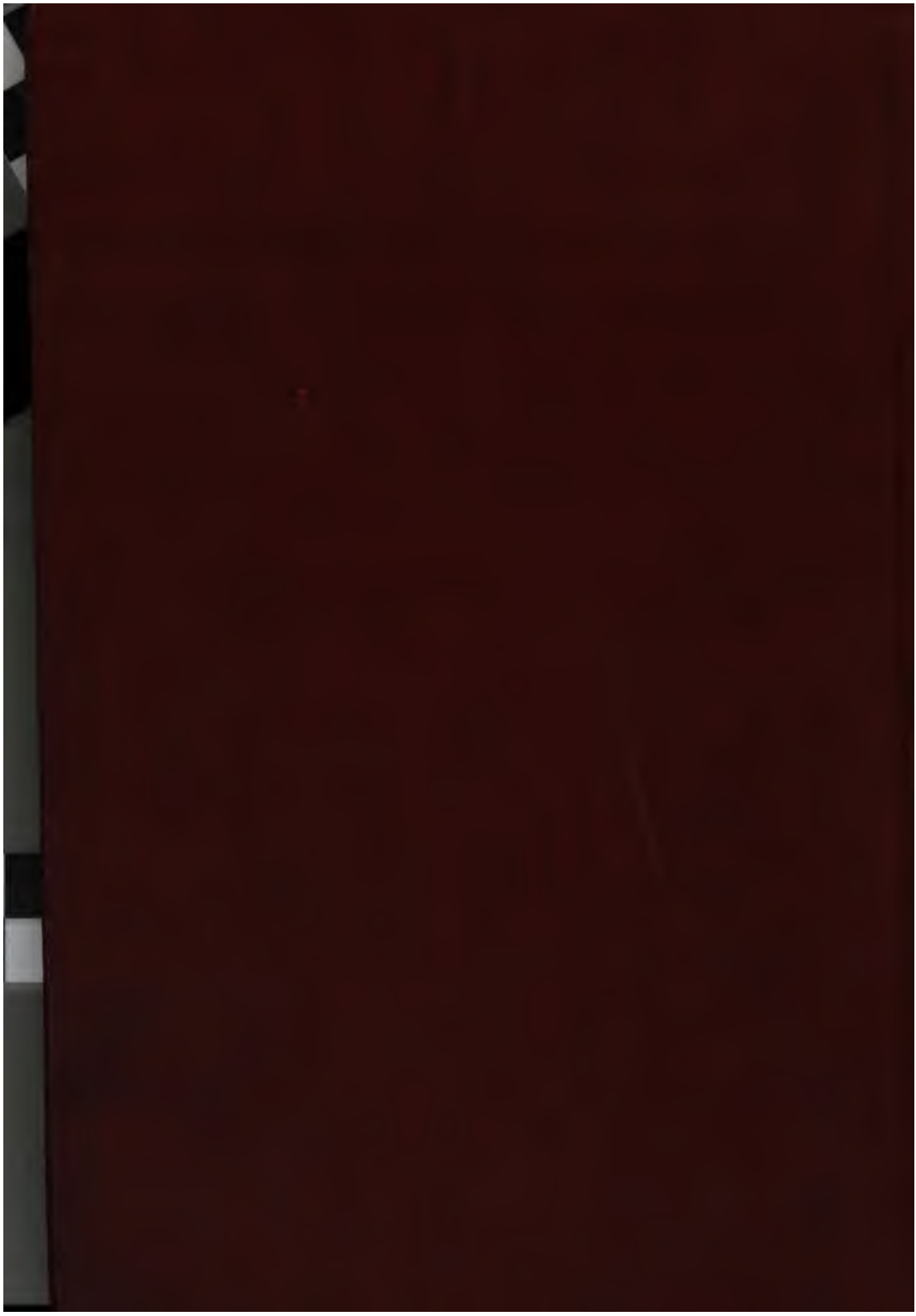
Illustrative Example. As a simple numerical illustration, assume that it has been determined that on a given east-and-west line the east-bound traffic is 3 times the west-bound traffic. Utilizing some of the data already worked out in article 201, assume that the ruling grade against east-bound traffic is 1.12 per cent, disregarding the pusher grade, and that, as computed, the Mikado engine can haul 16 loaded cars (50 tons load, 20 tons tare) up this grade. This car loading may also apply to one type of box car. The live load on one train (east-bound) is $16 \times 50 = 800$ tons. One-third of this (for west-bound traffic) is 267 tons, and adding $16 \times 20 = 320$ for tare, we have 587 tons as the weight of the revenue cars, west-bound. The tractive resistance on a level of these 16 cars is $(2.2 \times 587) + (16 \times 121.6) = 3247$ pounds. Adding 148 for the caboose and 1771 for the locomotive, we have 5166 as the total tractive resistance, and subtracting this from 35,174 we have 30,008 pounds available for grade. The total train weight is $157.5 + 587 + 12 = 756.5$ tons. Dividing this into 30,008 we have 39.6 pounds per ton, which is the equivalent of a 1.98-per-cent grade. On the 3:1 basis, the 1.98-per-cent grade against west-bound traffic corresponds to the 1.12-per-cent grade against east-bound traffic.

207. Estimation of Relative Traffic. The estimation of the relative volumes of traffic on a road yet to be constructed is usually a matter of sheer guesswork, except as it might be inferred from existing roads which are similar in character. But this problem often forms one of the features of the plans for the improvement of existing lines and in such a case there is an abundance of existing data. Since it concerns only the ruling grades, it affects only those trains which are affected by the rate of the ruling grade. It is unfortunately true that the fluctuations of traffic are such that a ratio which might have been perfect at the time of its computation may become considerably in error for a long period of time, if not permanently. A change in the development of the country may turn an agricultural region into a

manufacturing region or the discovery of vast deposits of coal or ore may result in a considerable and permanent change in the flow of traffic.

The Interstate Commerce Commission report for 1911–12 gives the following as the chief items of freight tonnage:

Bituminous coal	525 million tons
Ores	139 million tons
Lumber	125 million tons
Anthracite coal	119 million tons
Stone, sand, and other like articles	103 million tons
Grain	71 million tons
Cement, brick, and lime	62 million tons
Coke	62 million tons
30 other headings	580 million tons
Total	1,786 million tons

It will readily be seen that the above items only include the heavy, bulky freight. Such an item of manufacture as agricultural implements only weighed 3,399,214 tons, and household goods and furniture but little more. These figures emphasize the statements made above regarding the relative weights of various classes of traffic.

Perhaps the safest general rule is to say that opposite ruling grades should be made equal unless there is a definite reason for making them unequal. The reconstruction of the great trunk lines, on which so much money is now being spent, invariably aims at a lower grade against east-bound traffic than that allowed against the west-bound. The Canadian Pacific railroad had scarcely been completed before there was a reconstruction with this end in view. While it is one of the most uncertain elements to calculate, its justification under certain conditions is unquestionable.